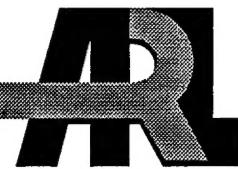


*ARMY RESEARCH LABORATORY*



# Investigation of Possible Decomposition of Alternative Fire-Extinguishing Agents Discharged Through a Vehicle Personnel Heater

Kevin L. McNesby  
Steven H. Modiano  
U.S. ARMY RESEARCH LABORATORY

Paul Marsh  
William Bolt  
Craig Herud  
U.S. ARMY ABERDEEN TEST CENTER

ARL-TR-1207

October 1996

19961104 013

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

DRAFT QUALITY IS UNPECIFIED

## **NOTICES**

Destroy this report when it is no longer needed. DO NOT return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.

# REPORT DOCUMENTATION PAGE

**Form Approved  
OMB No. 0704-0188**

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		October 1996	Final, Jun 95 - Jan 96
4. TITLE AND SUBTITLE  Investigation of Possible Decomposition of Alternative Fire-Extinguishing Agents Discharged Through a Vehicle Personnel Heater			5. FUNDING NUMBERS  PR: 1L161102AH43
6. AUTHOR(S)  Kevin L. McNesby, Steven H. Modiano, Paul Marsh,* William Bolt,* and Craig Herud*			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  U.S. Army Research Laboratory ATTN: AMSRL-WT-PC Aberdeen Proving Ground, MD 21005-5066		8. PERFORMING ORGANIZATION REPORT NUMBER  ARL-TR-1207	
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)		10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES  * U.S. Army Aberdeen Test Center, Aberdeen Proving Ground, MD 21005.			
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Approved for public release; distribution is unlimited.		12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  Fourier transform infrared (FT-IR) spectroscopy was used to monitor the possible thermal decomposition of alternative fire-extinguishing agents discharged through a vehicle personnel heater. The agent was introduced into the heater air induction port and flowed across the heat exchanger manifold. Gas samples were removed from the hot air output duct extension of the heater via stainless steel tubing and flowed through a 10-m path-length multipass optical gas cell placed in the sample beam of an FT-IR spectrometer. Five fire-extinguishing agents, CF <sub>3</sub> Br (trade name, Halon 1301), C <sub>3</sub> F <sub>7</sub> H (FM-200), C <sub>3</sub> F <sub>6</sub> H <sub>2</sub> (FE-36), C <sub>2</sub> F <sub>5</sub> H (FE-25), and CF <sub>3</sub> H (FE-13), were tested for two manifold temperatures of 380 and 480–510° C. No agent decomposition or combustion gas products could be detected for any of the agents tested under these temperature conditions. The agent decomposition products of interest were HF, HBr, CO, CF <sub>3</sub> H, C <sub>2</sub> H <sub>2</sub> , CH <sub>4</sub> , C <sub>2</sub> H <sub>4</sub> , and CF <sub>2</sub> O.			
14. SUBJECT TERMS  halons, thermal decomposition, FT-IR			15. NUMBER OF PAGES  41
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT  UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE  UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT  UNCLASSIFIED	20. LIMITATION OF ABSTRACT  UL

**INTENTIONALLY LEFT BLANK.**

## TABLE OF CONTENTS

	<u>Page</u>
<b>LIST OF FIGURES .....</b>	v
<b>1. INTRODUCTION .....</b>	1
<b>2. EXPERIMENTAL .....</b>	1
<b>3. RESULTS AND DISCUSSION .....</b>	4
<b>4. CONCLUSIONS .....</b>	19
<b>5. REFERENCES .....</b>	31
<b>DISTRIBUTION LIST .....</b>	33

**INTENTIONALLY LEFT BLANK.**

## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1.	Schematic diagram of the experimental setup used to collect the FT-IR absorption spectra. Air is heated by flowing over the gas flame enclosure .....	2
2.	Reference spectrum of HF generated with the HITRAN database. The parameters used to produce the spectrum are as follows: conc. = 10 ppm, T = 125° C .....	5
3.	Reference spectrum of HBr generated with the HITRAN database. The parameters used to produce the spectrum are as follows: conc. = 100 ppm, T = 125° C .....	6
4.	Reference spectrum of CF <sub>2</sub> O generated with the HITRAN database. The parameters used to produce the spectrum are as follows: conc. = 10 ppm, T = 125° C .....	7
5.	Reference spectrum of CO generated with the HITRAN database. The parameters used to produce the spectrum are as follows: conc. = 10 ppm, T = 125° C .....	8
6.	Reference spectrum of CF <sub>3</sub> H (FE-13) generated with the EPA database. The parameters used to produce the spectrum are not available .....	9
7.	Reference spectrum of CH <sub>4</sub> generated with the HITRAN database. The parameters used to produce the spectrum are as follows: conc. = 10 ppm, T = 125° C .....	10
8.	Reference spectrum of C <sub>2</sub> H <sub>2</sub> generated with the HITRAN database. The parameters used to produce the spectrum are as follows: conc. = 10 ppm, T = 125° C .....	11
9.	Reference spectrum of C <sub>2</sub> H <sub>4</sub> generated with the QaSoft database. The parameters used to produce the spectrum are as follows: conc. = 100 ppm-m, T = 25° C .....	12
10.	Reference spectrum of CF <sub>3</sub> Br (Halon 1301) generated from the QaSoft database. The parameters are 100 ppm-m at 25° C .....	13
11.	Reference spectrum of C <sub>3</sub> F <sub>7</sub> H (FM-200) measured in our laboratory .....	14
12.	Reference spectrum of C <sub>2</sub> F <sub>5</sub> H generated with the QaSoft database. The parameters used to produce the spectrum are as follows: conc. = 100 ppm-m, T = 25° C .....	15
13.	The infrared absorbance spectrum of gas removed from the vicinity of a JP-8 fuel pool fire 15 s after the application of approximately 0.5 kg of CF <sub>3</sub> Br .....	16
14.	Expanded regions of the infrared absorbance spectrum of gas removed from the vicinity of a JP-8 fuel pool fire 15 s after the application of approximately 0.5 kg CF <sub>3</sub> Br (Halon 1301) .....	17
15.	Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire extinguishing agent Halon 1301 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380° C .....	18

<u>Figure</u>	<u>Page</u>
16. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent Halon 1301 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510° C .....	20
17. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FM-200 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380° C .....	21
18. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FM-200 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510° C .....	22
19. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-36 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380° C .....	23
20. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-36 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510° C .....	24
21. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-25 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380° C .....	25
22. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-25 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510° C .....	26
23. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-13 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380° C .....	27
24. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-13 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510° C .....	28

## 1. INTRODUCTION

The cessation of the production and sale of ozone-depleting halogenated hydrocarbons (halons) (e.g.,  $\text{CF}_3\text{Br}$  - Halon 1301) has increased the effort of finding suitable replacements (Wray 1992; Philipczak 1993). However, researchers face formidable obstacles in developing a product that equals the firefighting capabilities of halons. Among the main criteria for the suitability of a halon alternative are: (1) it must be as effective at extinguishing fires as those agents it replaces, (2) it must be economically viable, (3) its ozone-depletion factor should be lower than 0.2, the level that must be met by the year 2000 under current proposed regulations (halons have ozone-depletion factors ranging from 3 to 10) (Federal Register 1992), and (4) human tolerance for the chemical must be high for the conditions where it is employed.

Recently, this laboratory reported the results of a Fourier transform infrared (FT-IR) spectroscopic investigation of the toxic gases produced during the inhibition of JP-8 fuel fires by  $\text{CF}_3\text{Br}$  (Halon 1301) and  $\text{C}_3\text{F}_7\text{H}$  (FM-200) (Modiano et al., to be published). It was shown that, in JP-8 fires inhibited by either agent, toxic gas products were generated that pose serious health risks to the personnel exposed to the combustion gases. For each agent tested, the principal toxic gases produced during inhibition of JP-8 fires were  $\text{CF}_2\text{O}$  and HF. For JP-8 fires inhibited by  $\text{CF}_3\text{Br}$ , a surprising high level of HBr was also produced.

The current work continues the investigation of the potential toxic decomposition and combustion products formed during the application of fire-extinguishing agents under specific working conditions. There had been concern that military vehicles equipped with fuel-fired personnel heaters are capable of producing toxic gases when fire-extinguishing agents are flowed across the hot heat exchanger manifold of the heater. FT-IR absorption spectroscopy was used to measure spectra of gases removed from the hot air output duct of the heater, while the fire-extinguishing agent was introduced into the heater air induction port. Five fire-extinguishing agents were tested: Halon 1301 ( $\text{CF}_3\text{Br}$ ), FE-25 ( $\text{C}_2\text{F}_5\text{H}$ ), FM-200 ( $\text{C}_3\text{F}_7\text{H}$ ), FE-13 ( $\text{CF}_3\text{H}$ ), and FE-36 ( $\text{C}_3\text{F}_6\text{H}_2$ ).

## 2. EXPERIMENTAL

The schematic diagram representing the experimental setup is given in Figure 1. A vehicular compartment heater (multifuel burning, NSN-2540-01-169-5159, S/N 11882, manufactured by Stewart-

# Schematic of Vehicular Compartment Heater

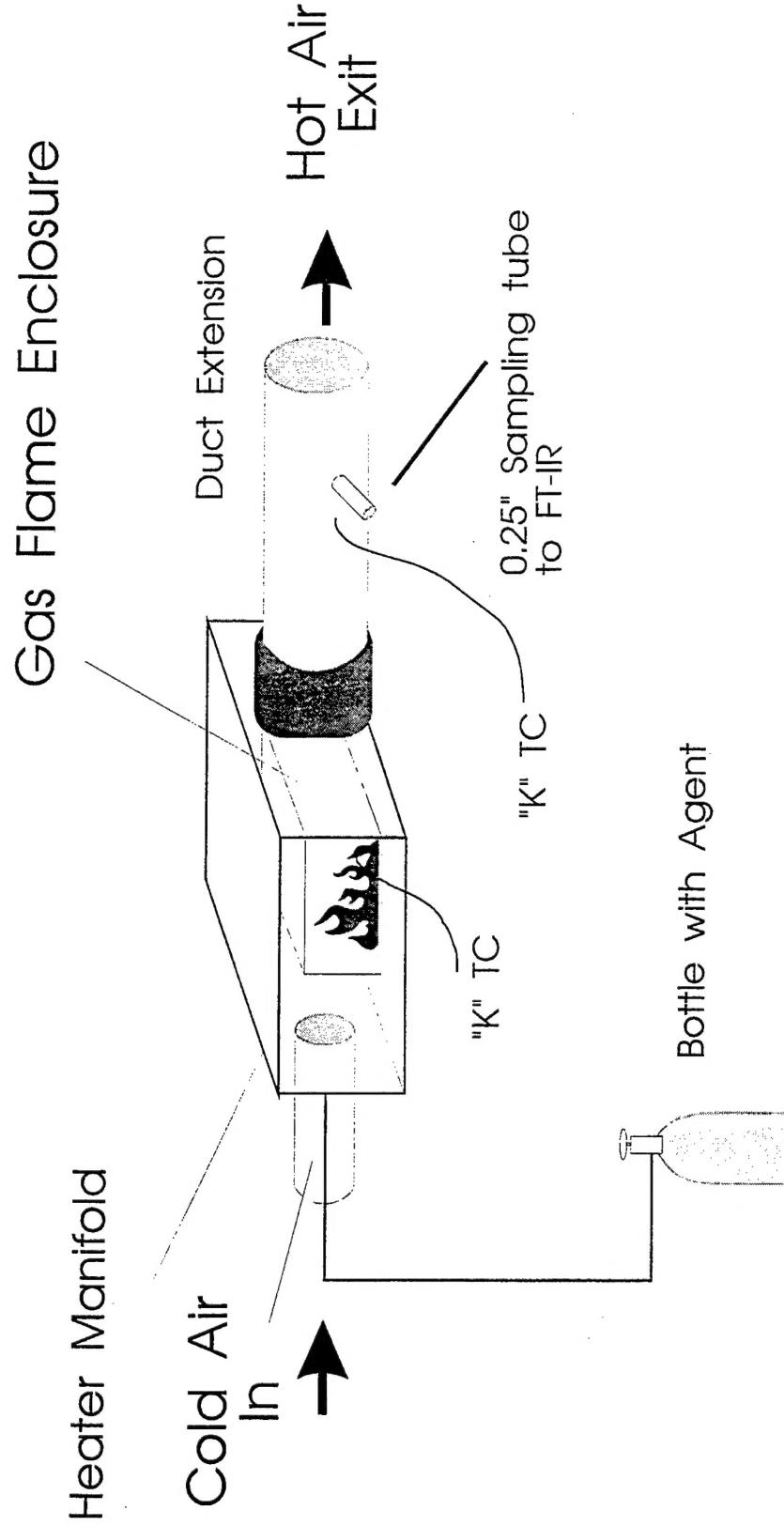


Figure 1. Schematic diagram of the experimental setup used to collect the FT-IR absorption spectra. Air is heated by flowing over the gas flame enclosure.

test stand (see Figure 1). The test was performed outdoors. Infrared spectra of gases removed from the hot air output duct of the personnel heater were measured using a Midac Corporation Model G-5001-FH Fourier transform spectrometer system operating at  $0.5\text{-cm}^{-1}$  resolution. Detection of the infrared radiation was by a liquid nitrogen-cooled Hg-Cd-Te detector. The interior of the spectrometer was purged with dry nitrogen. The spectrometer was ruggedized for outdoor use by the manufacturer. The gas samples were removed from the hot air output duct via a 0.25-in-diameter stainless steel tube in series with a 10-m path-length multipass optical cell and a mechanical vacuum pump. The distance between the hot air output duct and the spectrometer was 5 m. The gas samples were continuously flowed through a 10-m path-length multipass optical gas cell (internal volume approximately  $2,300\text{ cm}^3$ ) contained within the FT-IR spectrometer. The multipass cell was maintained at a constant temperature of  $125^\circ\text{ C}$ .

A "K" type thermocouple (chromel-alomel) was mounted on the body of the personnel heater heat exchanger. Another "K" type thermocouple was installed in the exhaust duct approximately 42 in from the exit. A third "K" type thermocouple was installed to measure the ambient air temperature. The airflow through the system was measured using a Kurtz Model 441-S Air Velocity Meter inserted into the duct parallel to the airflow. The airflow was measured with the heater air induction blower on and the heater element turned off. The temperature-corrected airflow for this test was calculated to be 660 cfm at  $495^\circ\text{ C}$ .

The personnel heater was ignited and allowed to operate until the heat exchanger surface and hot air output temperatures had stabilized. After the heater temperature had stabilized, but before the introduction of the agent into the heater air induction port, gas flow from the probe through the spectrometer optical system was begun by opening a valve between the vacuum pump and the exit port of the multipass optical cell. Upon establishment of gas flow from the heater hot air output duct through the sampling tube and the multipass optical cell, acquisition of spectra was begun, with each spectrum consisting of 10 co-added scans measured at  $0.5\text{ cm}^{-1}$  resolution. The time required for collection of each 10-scan spectrum was approximately 15 s. Approximately 1 min after data acquisition was begun, chemical agent was allowed to flow through the heater air induction port, across the heat exchanger, and out the hot air output duct. Because of differences in viscosity and density, flow rate varied for each agent tested. Chemical agent flow was stopped after 4 liters of agents at a flow rate of 2 liters/min had been delivered. The FT-IR spectrometer continued to acquire spectra until no trace of agent could be observed in the spectra, after which the data acquisition was halted. Five fire-extinguishing agents ( $\text{CF}_3\text{Br}$  [tradename, Halon 1301],

All interferograms were transformed using triangular apodization, and the resulting single-beam infrared spectra ratioed to a spectrum measured prior to the chemical agent being introduced into the system.

### 3. RESULTS AND DISCUSSION

Figures 2–9 show infrared spectra (Rothman et al. 1992; National Institute of Standards and Technology 1992; Infrared Analysis, Inc. 1995) of the expected possible decomposition or combustion products for the fire-extinguishing agents tested. These products are HF, HBr, HC1, CF<sub>3</sub>H, C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, CH<sub>4</sub>, and CF<sub>2</sub>O. Figures 10–12 are spectra of the agents Halon 1301 (CF<sub>3</sub>Br), FM-200 (C<sub>3</sub>F<sub>7</sub>H), and FE-25 (C<sub>2</sub>F<sub>5</sub>H). Note that the possible decomposition product CF<sub>3</sub>H shown in Figure 6 is the agent FE-13.

As an example of gases produced during chemical suppression of large-scale "real" fires, Figure 13 shows the infrared absorbance spectrum of a gaseous sample removed from a JP-8 fuel fire burning in air, after the application of a small amount of the fire inhibitor CF<sub>3</sub>Br. Figure 14 presents the same data as Figure 13 but with spectral regions expanded for analysis. These spectra are shown for comparison with the present work. Evident in Figure 14 are the spectral features due to the hydrocarbon-fueled (JP-8) fire (i.e., H<sub>2</sub>O, CO<sub>2</sub>, CO, CH<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, and C<sub>2</sub>H<sub>4</sub>). Also present in this spectrum are the absorption features of the fire inhibitor CF<sub>3</sub>Br, and the halon decomposition products HF, HBr, HC1, CF<sub>3</sub>H, and CF<sub>2</sub>O. The source of the HC1 is believed to be chlorine impurities in the CF<sub>3</sub>Br.

Figure 15 shows the infrared absorption spectrum of a gaseous sample removed from the personnel heater hot air output duct, during flow of Halon 1301 through the heater air induction port, while the heater manifold temperature was maintained at 380° C. Evident in this spectrum are intense absorptions of the fundamental bands for CF<sub>3</sub>Br at 760, 1,080, and 1,200 cm<sup>-1</sup>. These absorptions are saturated (i.e., there was sufficient agent concentration in the optical path to absorb all infrared radiation at frequencies corresponding to agent fundamental vibrations). Also evident in the spectrum are absorptions from CO<sub>2</sub> and H<sub>2</sub>O. Within the limits of detection of the instrument, no evidence for the decomposition or combustion products of CF<sub>3</sub>Br, HF, HBr, HC1, CF<sub>3</sub>H, CO, CF<sub>2</sub>O, C<sub>2</sub>H<sub>2</sub>, or C<sub>2</sub>H<sub>4</sub> was seen.

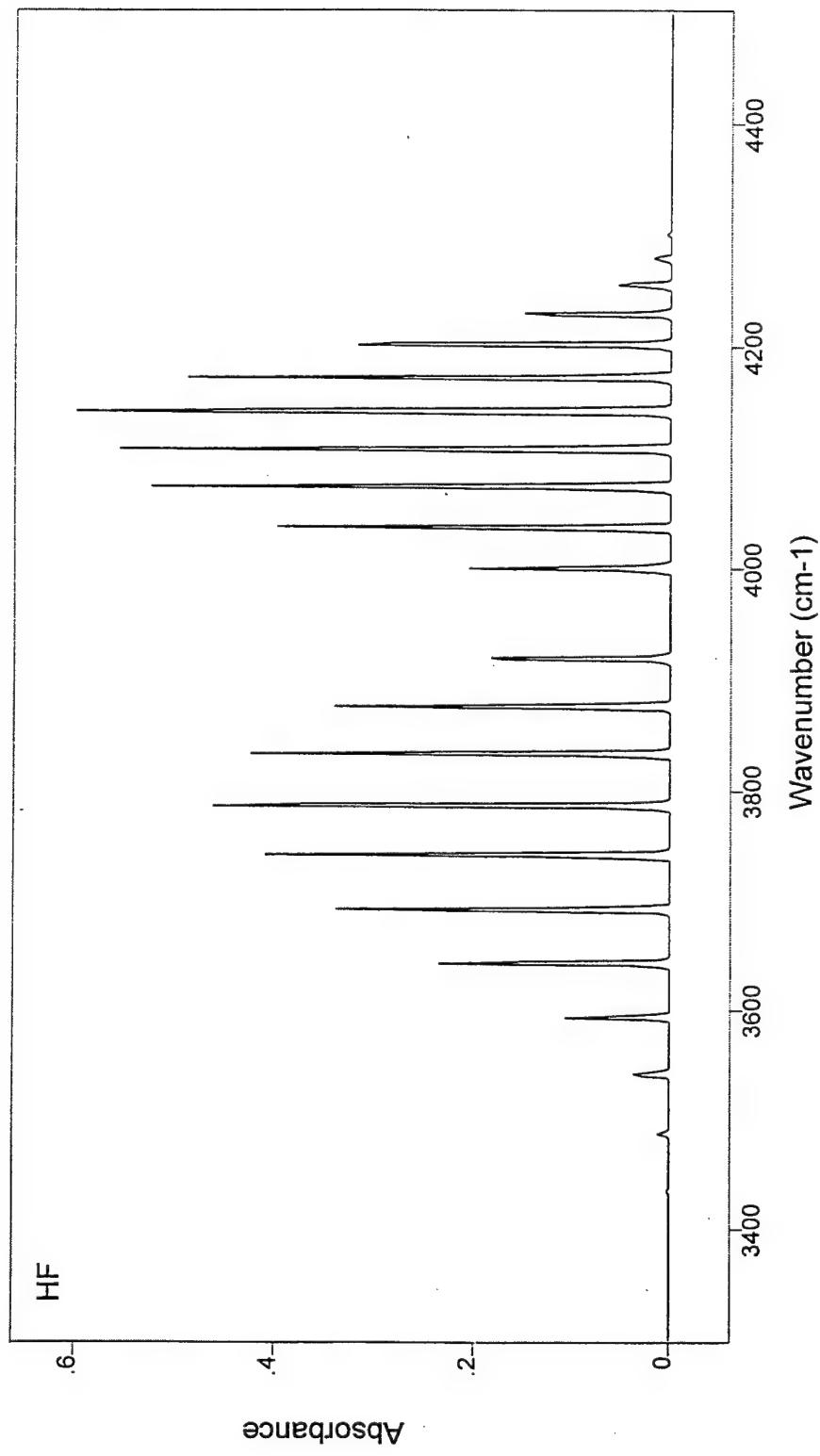


Figure 2. Reference spectrum of HF generated with the HITRAN database. The parameters used to produce the spectrum are as follows: conc. = 10 ppm, T = 125° C.

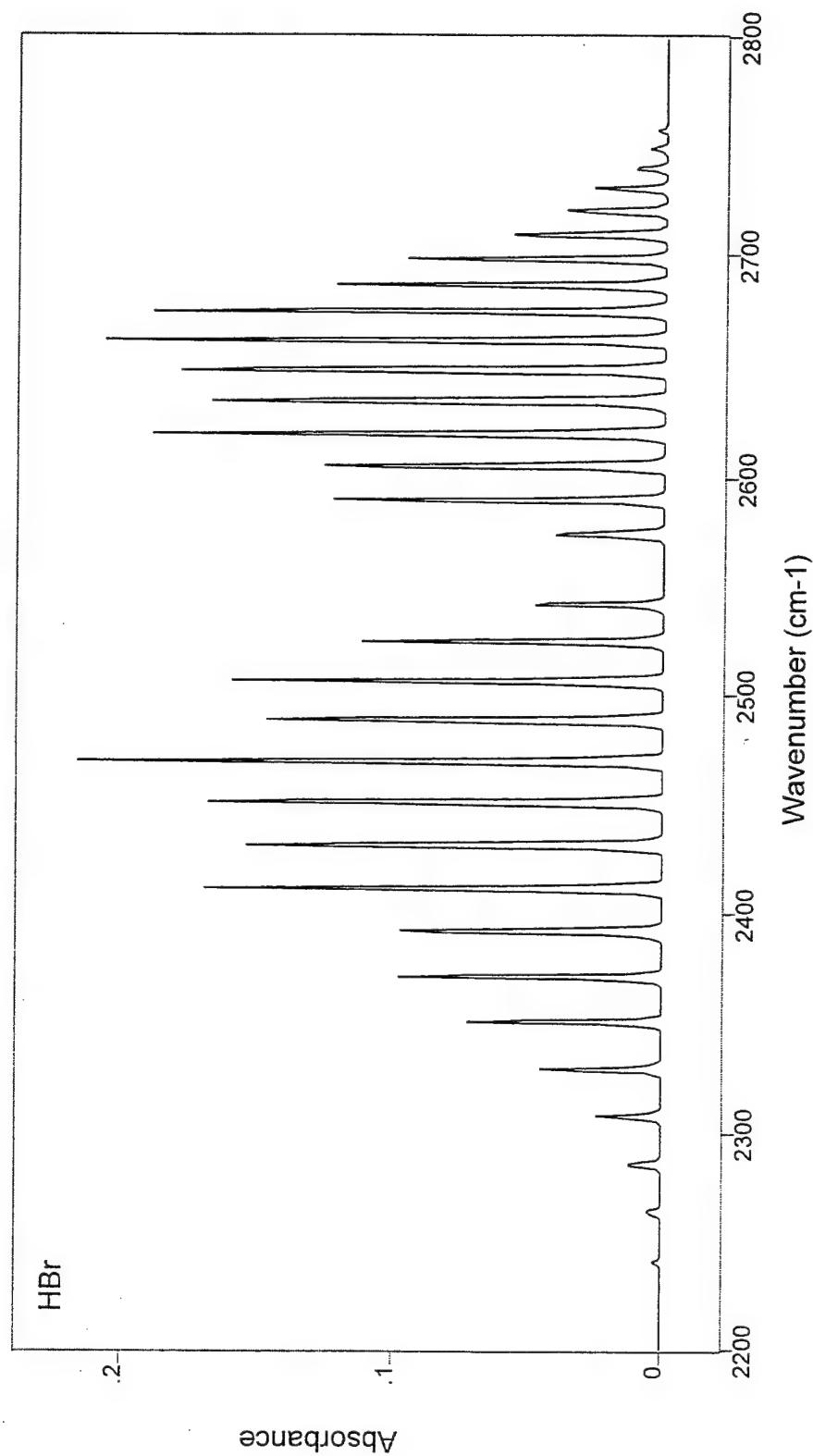


Figure 3. Reference spectrum of HBr generated with the HITRAN database. The parameters used to produce the spectrum are as follows: conc. = 100 ppm, T = 125° C.

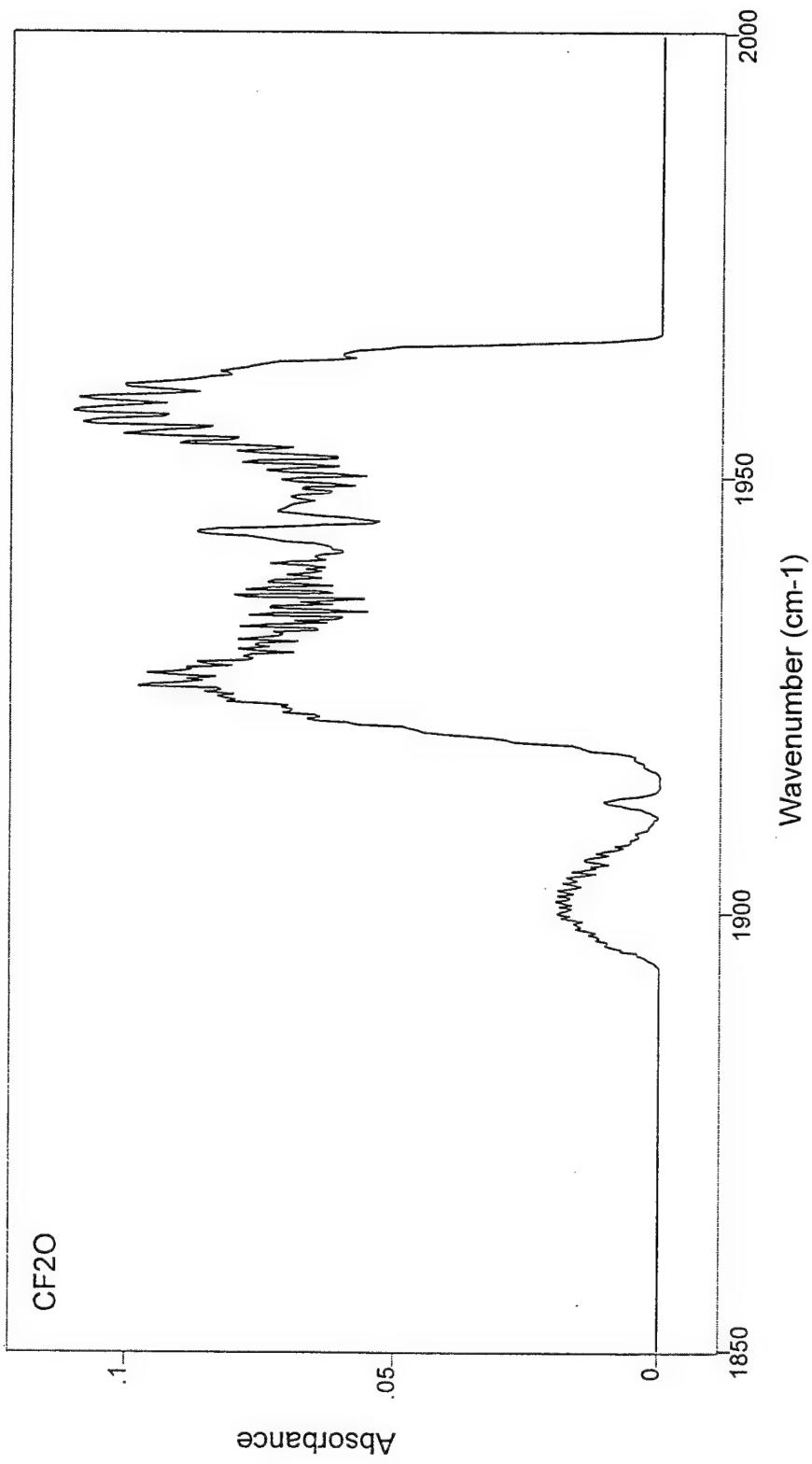


Figure 4. Reference spectrum of  $\text{CF}_2\text{O}$  generated with the HITRAN database. The parameters used to produce the spectrum are as follows:  
conc. = 10 ppm, T = 125° C.

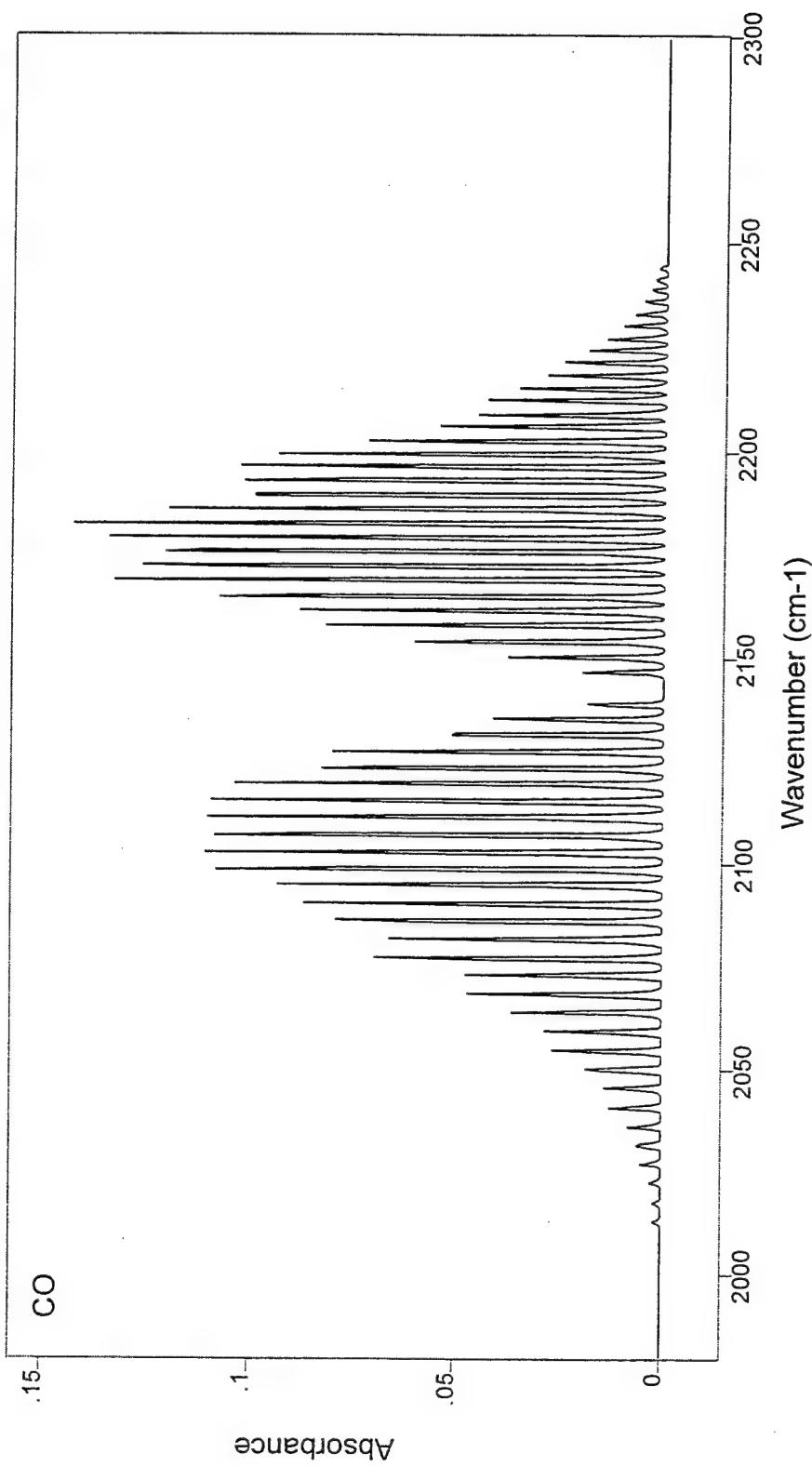


Figure 5. Reference spectrum of CO generated with the HITRAN database. The parameters used to produce the spectrum are as follows:  
conc. = 10 ppm, T = 125° C.

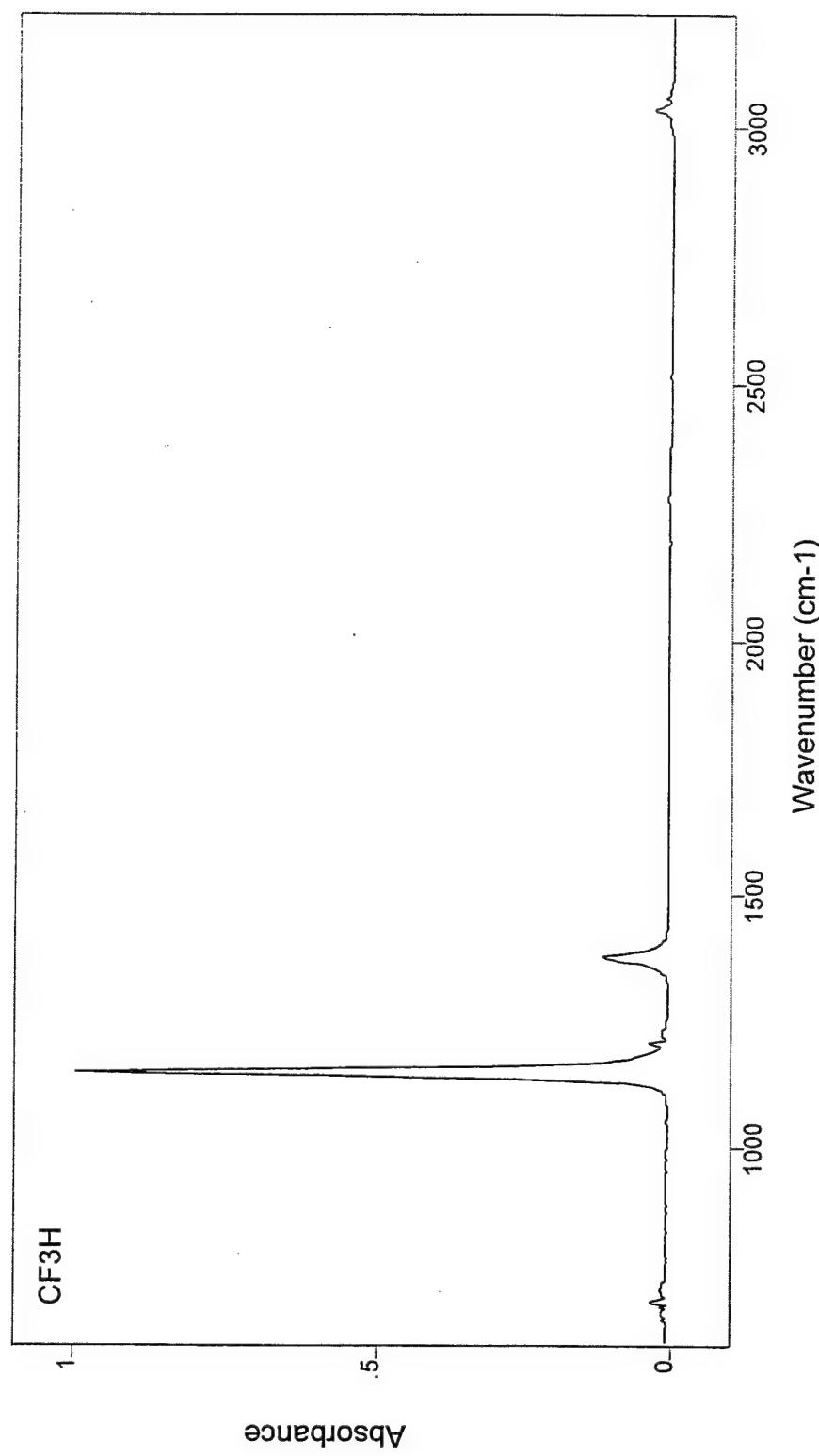


Figure 6. Reference spectrum of  $\text{CF}_3\text{H}$  (FE-13) generated with the EPA database. The parameters used to produce the spectrum are not available.

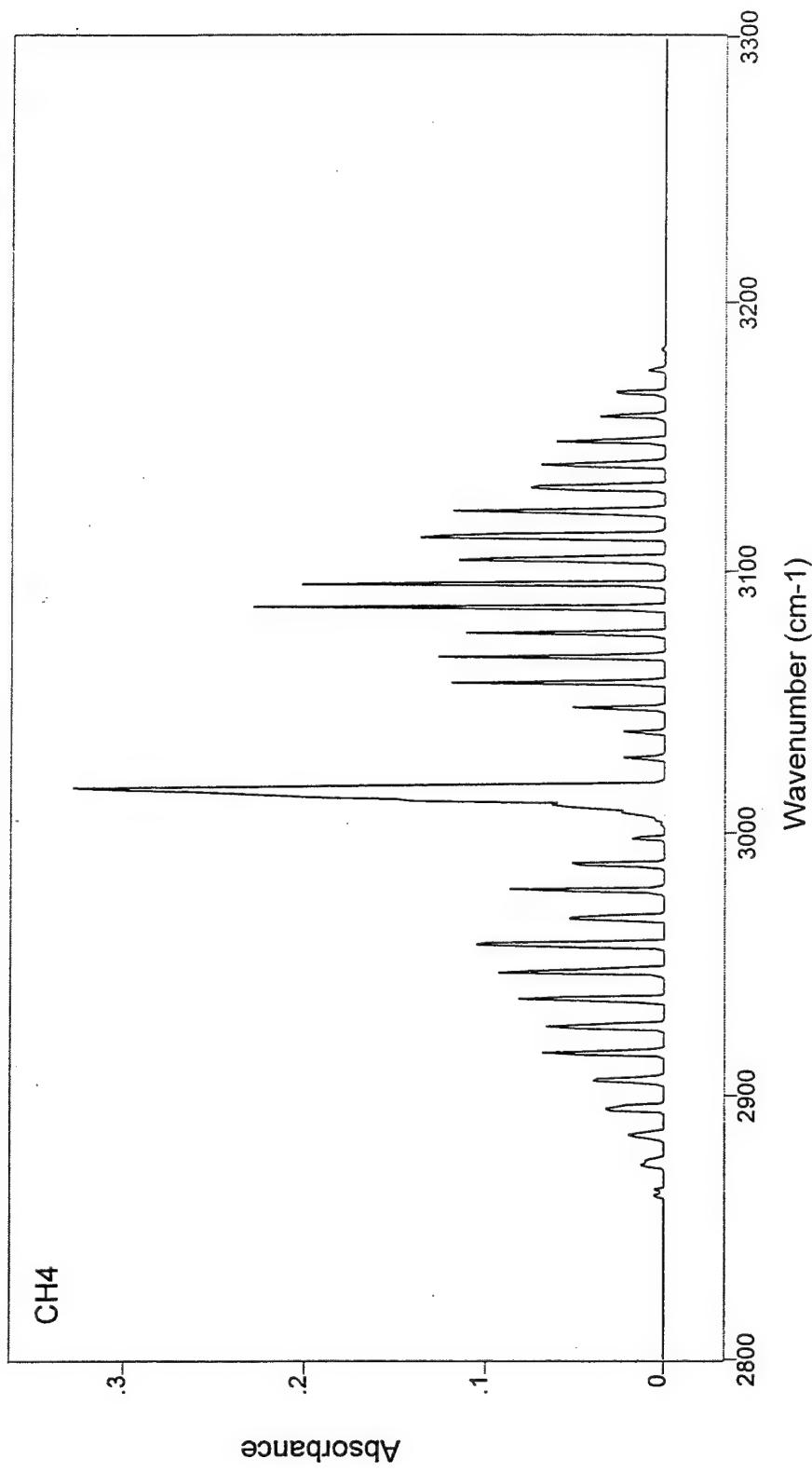


Figure 7. Reference spectrum of CH<sub>4</sub> generated with the HITRAN database. The parameters used to produce the spectrum are as follows:  
conc. = 10 ppm, T = 125° C.

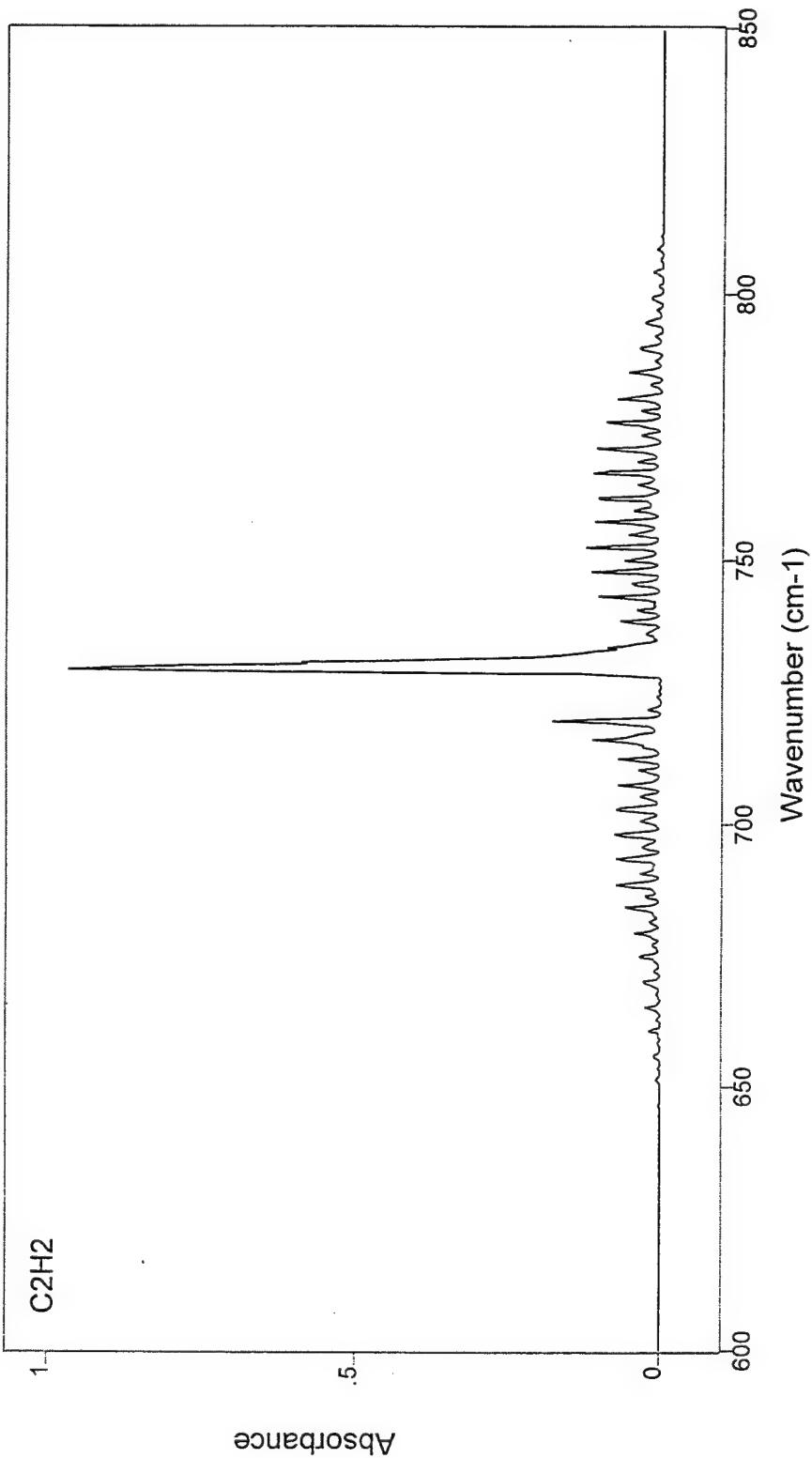


Figure 8. Reference spectrum of  $\text{C}_2\text{H}_2$  generated with the HITRAN database. The parameters used to produce the spectrum are as follows:  
conc. = 10 ppm, T = 125° C.

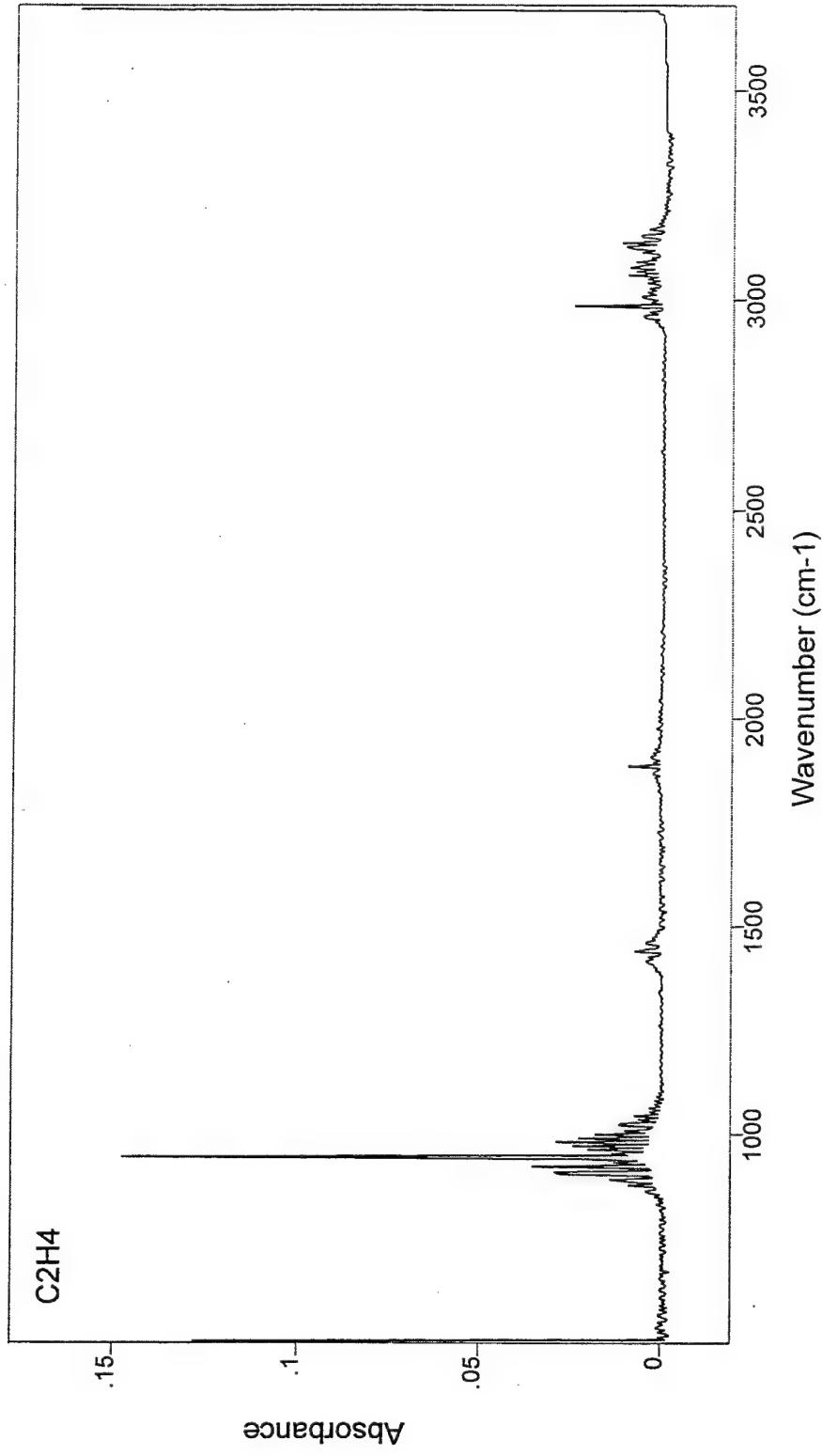


Figure 9. Reference spectrum of C<sub>2</sub>H<sub>4</sub> generated with the QaSoft database. The parameters used to produce the spectrum are as follows: conc. = 100 ppm-m, T = 25° C.

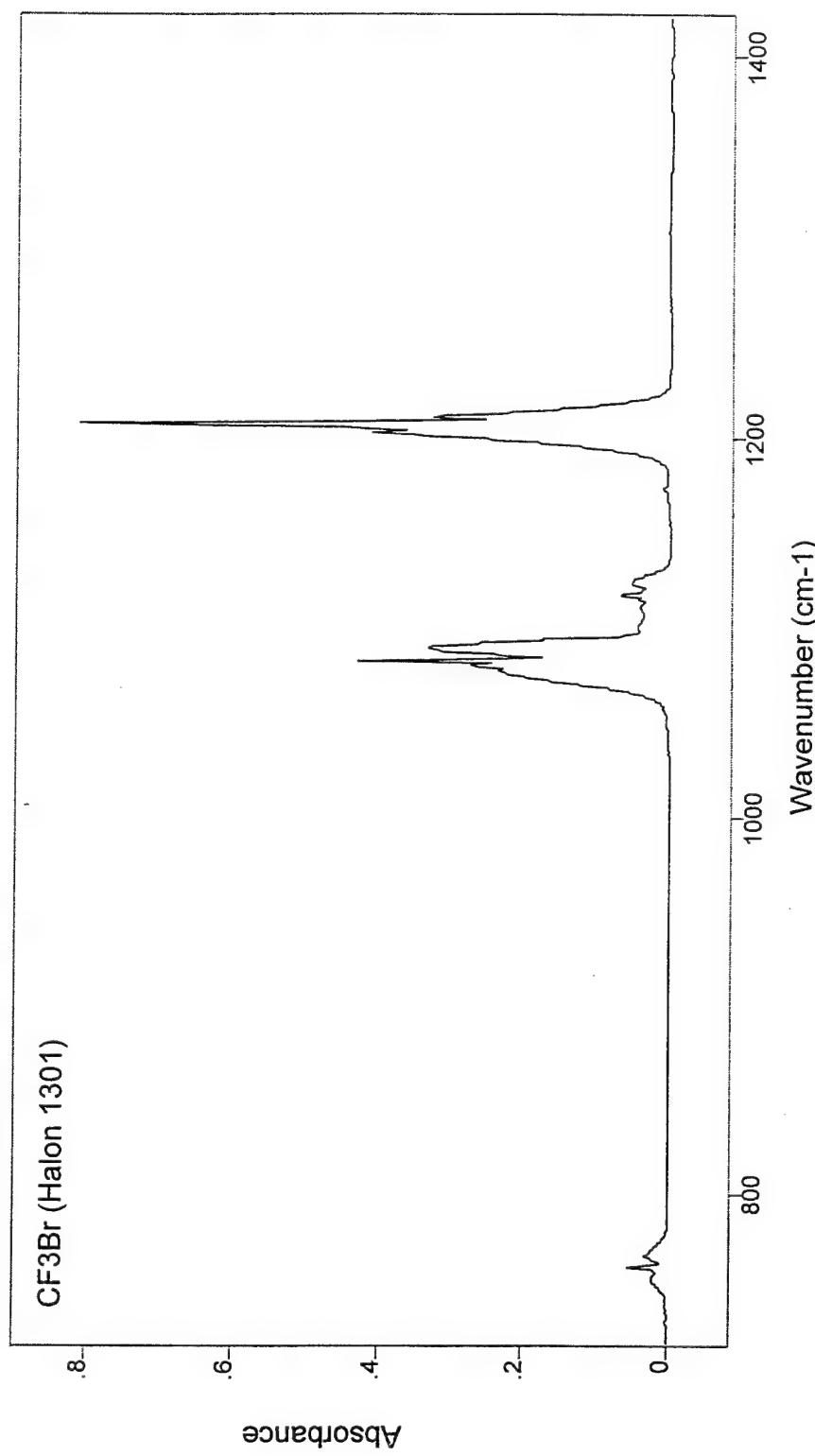


Figure 10. Reference spectrum of CF<sub>3</sub>Br (Halon 1301) generated from the QaSoft database. The parameters are 100 ppm-m at 25° C.

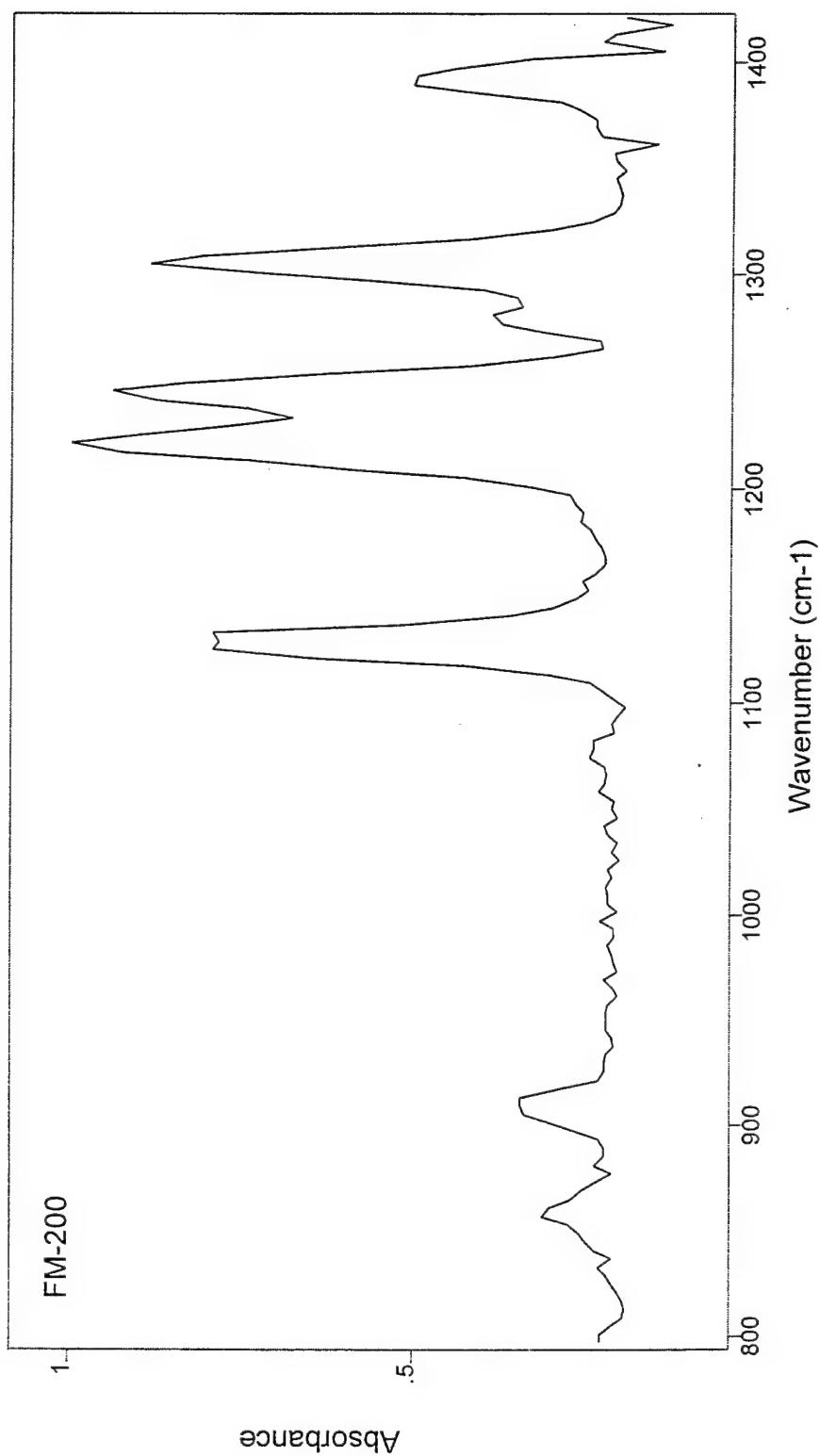


Figure 11. Reference spectrum of  $\text{C}_3\text{F}_7\text{H}$  (FM-200) measured in our laboratory.

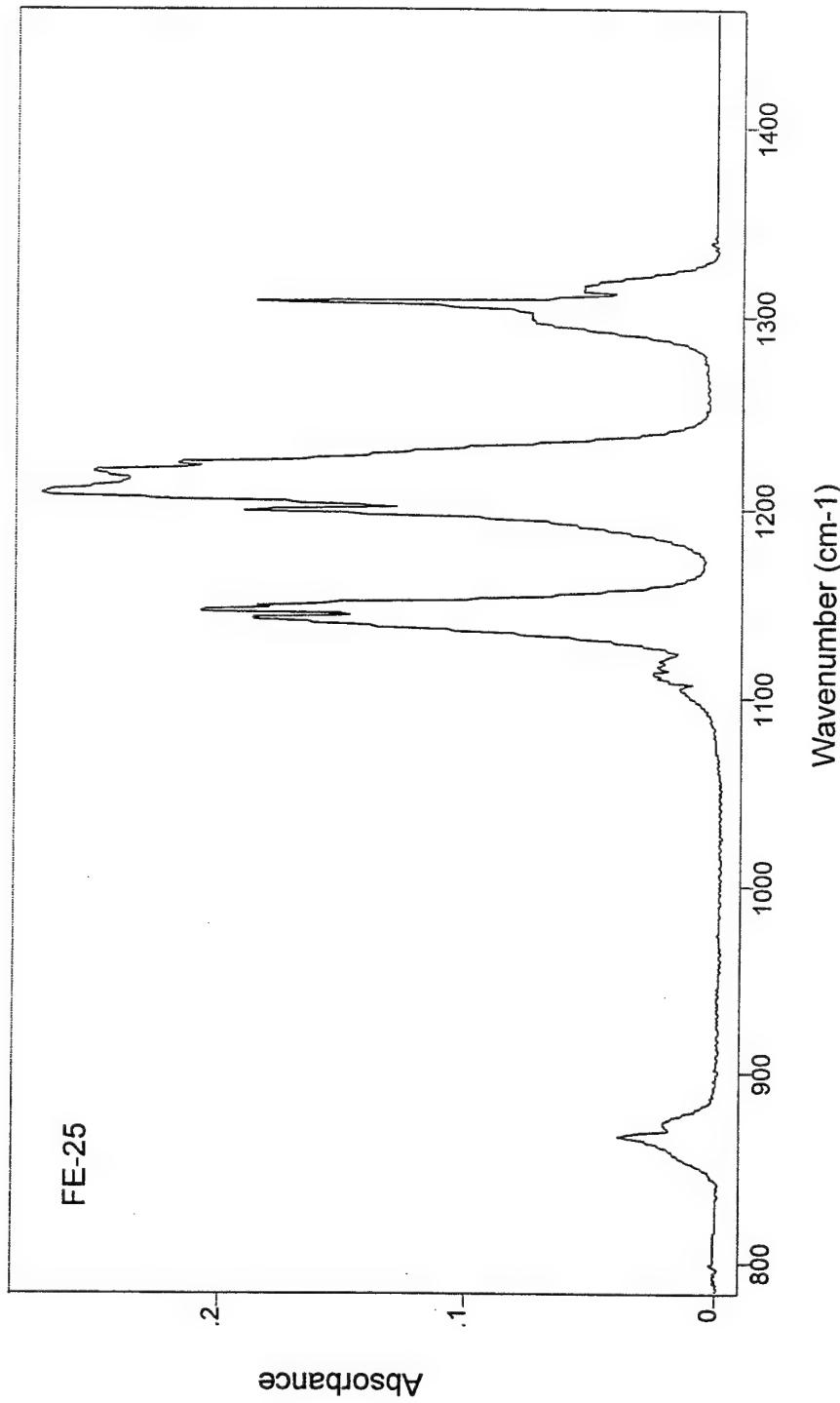


Figure 12. Reference spectrum of  $C_2E_5H$  (FE-25) from the QaSoft database. The parameters used to produce the spectrum are as follows: conc. = 100 ppm-m, T = 25° C.

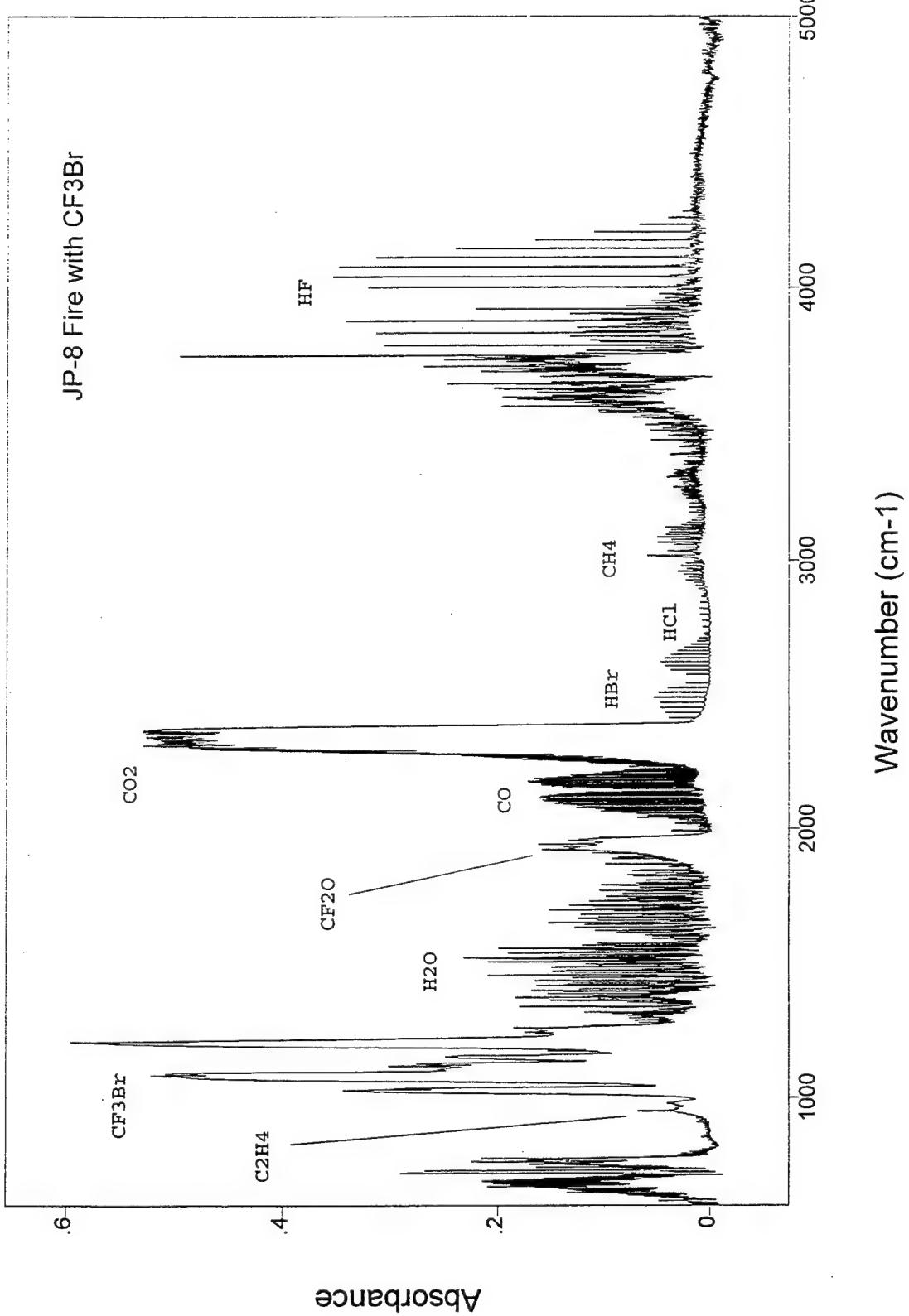


Figure 13. The infrared absorbance spectrum of gas removed from the vicinity of a JP-8 fuel pool fire 15 s after the application of approximately 0.5 kg of CF<sub>3</sub>Br.

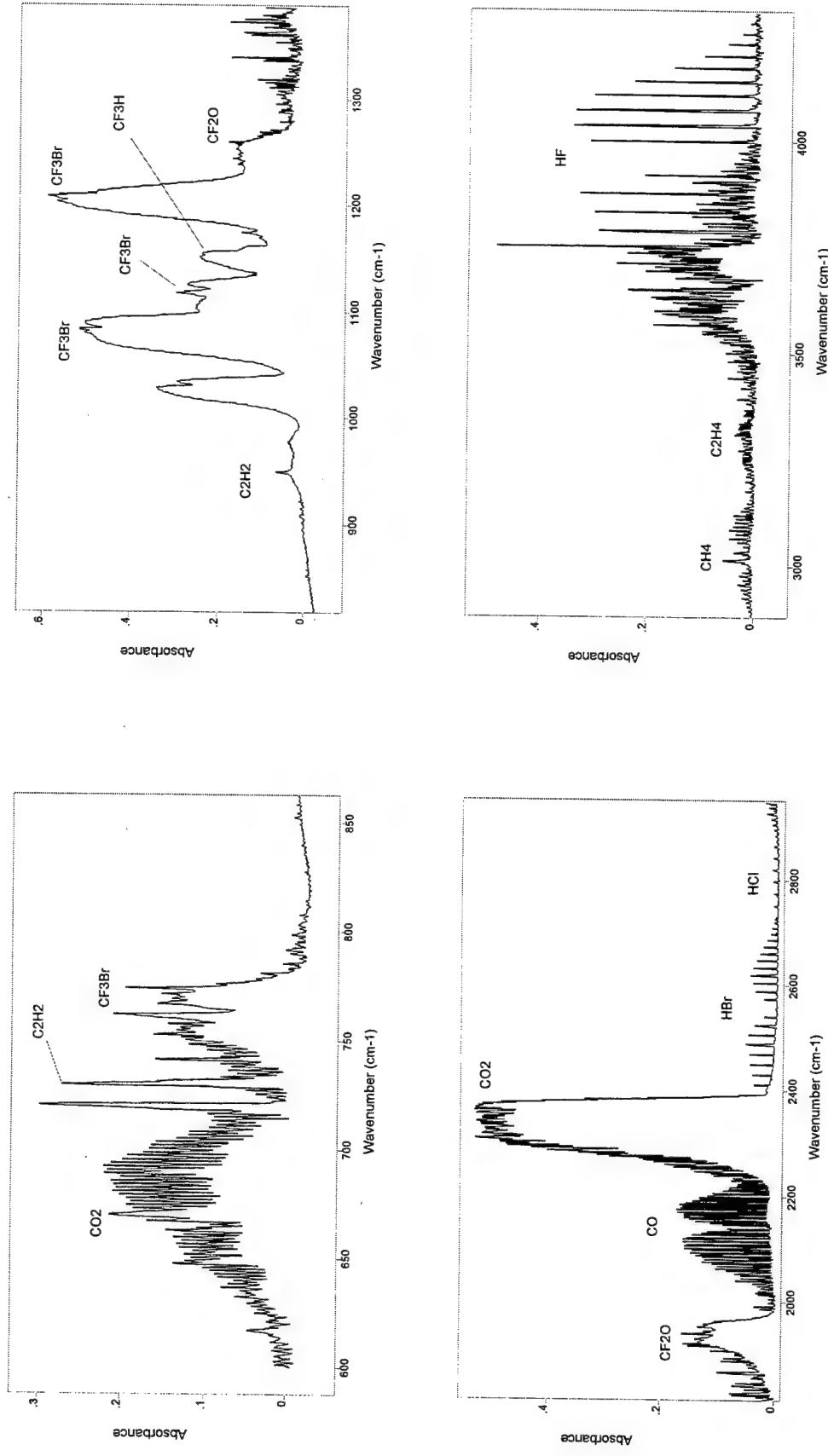
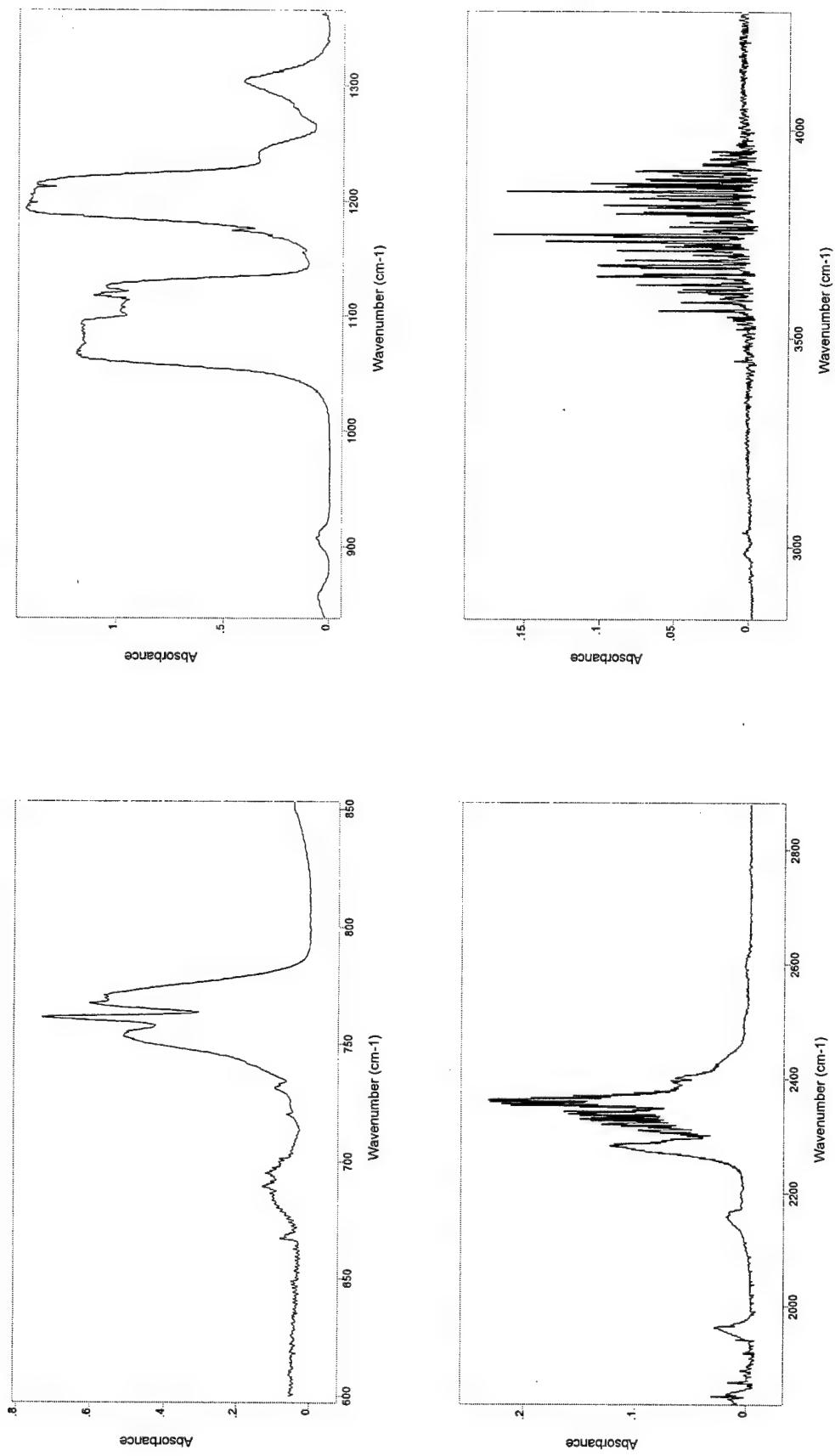


Figure 14. Expanded regions of the infrared absorbance spectrum of gas removed from the vicinity of a JP-8 fuel pool fire 15 s after the application of approximately 0.5 kg CF<sub>3</sub>Br (Halon 1301).



**Figure 15. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent Halon 1301 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380° C.**

Figure 16 shows the infrared absorption spectrum of a gaseous sample removed from the personnel heater hot air output duct, during flow of Halon 1301 through the heater air induction port, while the heater manifold temperature was maintained at 510° C. This spectrum is similar to that measured for the analogous experiment at 380° C. Again, within the limits of detection for the instrument, no evidence of the decomposition products of Halon 1301 was seen.

Figures 17–24 present similar results for FM-200, FE-36, FE-25, and FE-13 for both temperature ranges used in these tests. Again, within the limits of detection for the instrument, no evidence of agent decomposition or combustion products ( $\text{CF}_3\text{Br}$ , HF, HBr, HC1,  $\text{CF}_3\text{H}$ , CO,  $\text{CF}_2\text{O}$ ,  $\text{C}_2\text{H}_2$ , or  $\text{C}_2\text{H}_4$ ) was seen.

A closer examination of the spectra of FM-200, FE-36, FE-25, and FE-13 revealed an unexpected consequence of the methodology used in the study. With the exception of Halon 1301 (the first gas to be studied), all subsequent agents were contaminated with the previous agent that was in the system. The order in which the agents were studied for both temperature conditions was as follows: Halon 1301, FM-200, FE-36, FE-25, FE-13, and then Halon 1301 was repeated. This sequence was done for the lower temperature and then repeated for the higher temperature. This contamination problem was caused by improperly evacuating the gas cylinder used to hold the fire-extinguishing agent before it was refilled with the next agent to be tested.

Table 1 presents the minimum detection limits for each of the decomposition products of interest under the experimental conditions employed for these tests. The detection limit was defined as a spectral feature with a peak intensity three times larger than the peak-to-peak noise (in transmission). The detection limit was calculated using this peak intensity value and spectral parameters from the HITRAN92 Database (Rothman et al. 1992), for the species under consideration.

#### 4. CONCLUSIONS

Five fire-extinguishing agents,  $\text{CF}_3\text{Br}$ ,  $\text{C}_3\text{F}_7\text{H}$ ,  $\text{C}_3\text{F}_6\text{H}_2$ ,  $\text{C}_2\text{F}_5\text{H}$ , and  $\text{CF}_3\text{H}$ , were tested for possible decomposition after being discharged into the air induction port of a fuel-fired vehicle personnel heater. Gas samples removed from the personnel heater hot air output duct, while fire-extinguishing agents were flowed across the heat exchanger manifold, were examined using FT-IR spectroscopy. Within the limits of detection for the instrument, no evidence of agent decomposition or combustion products (HF, HBr, HC1,  $\text{CF}_3\text{H}$ , CO,  $\text{CF}_2\text{O}$ ,  $\text{C}_2\text{H}_2$ , or  $\text{C}_2\text{H}_4$ ) was measured in these systems under the conditions of the test.

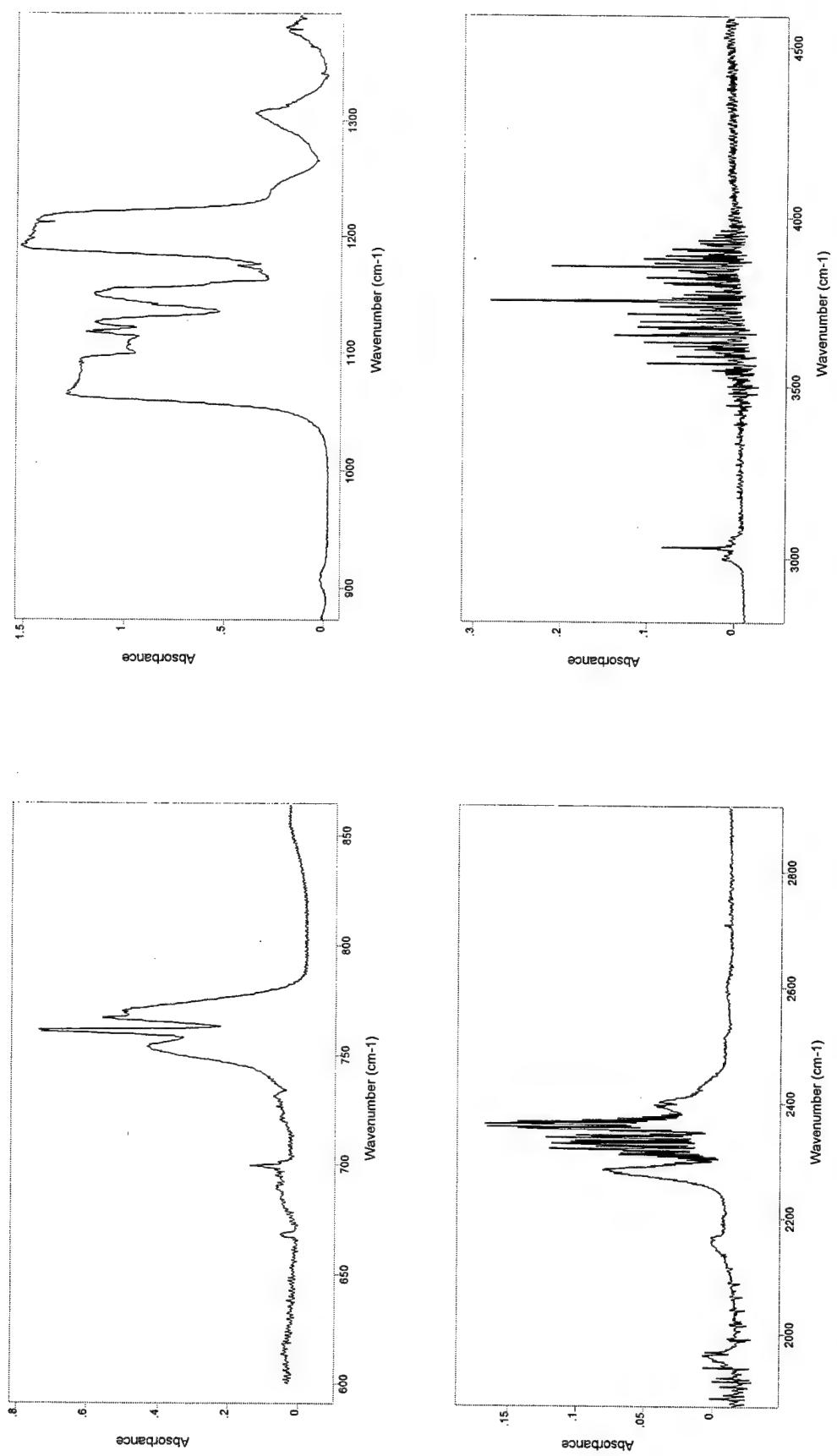
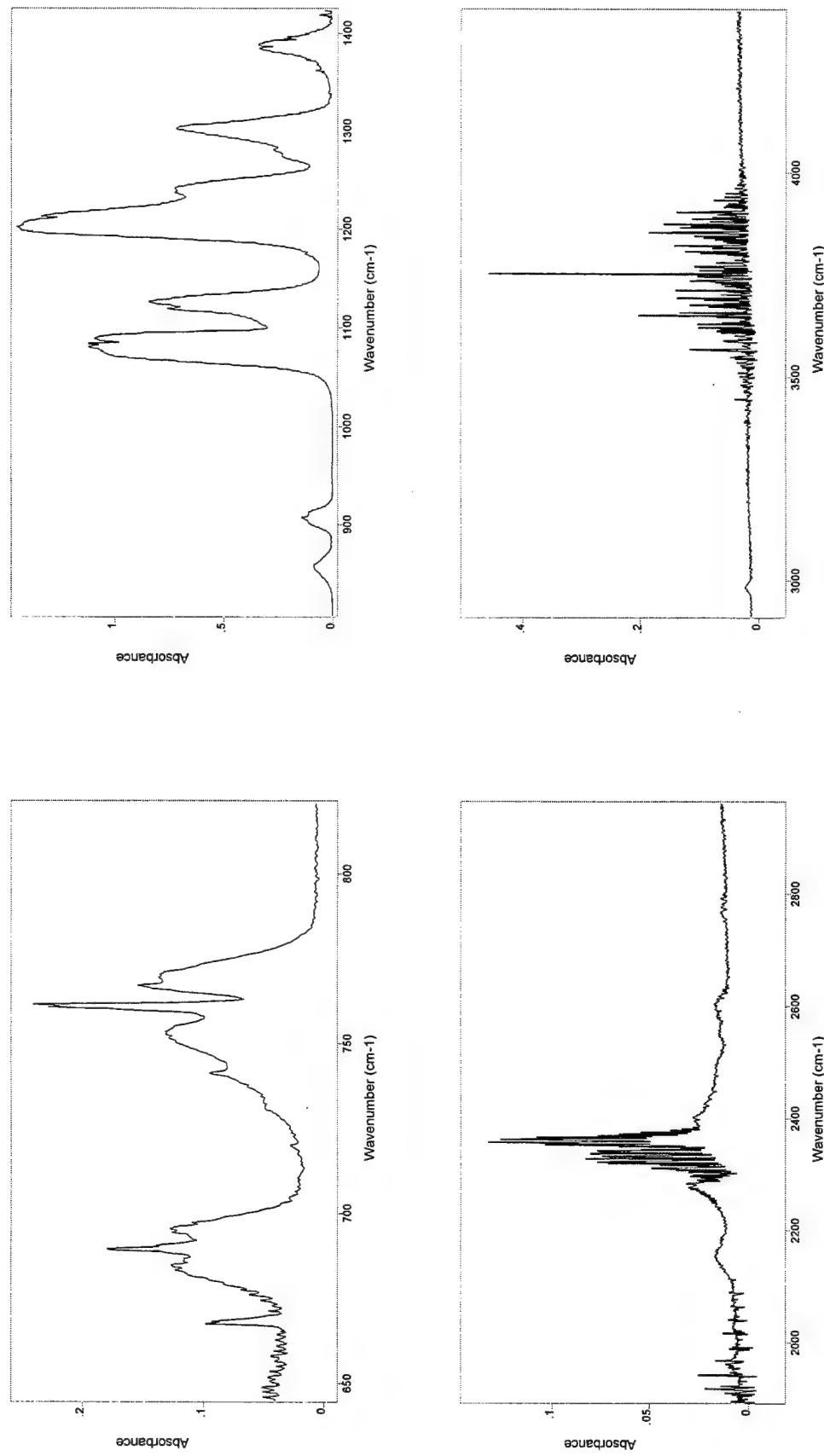


Figure 16. Expanded regions of the absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent Halon 1301 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510°C.



**Figure 17.** Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FM-200 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380°C.

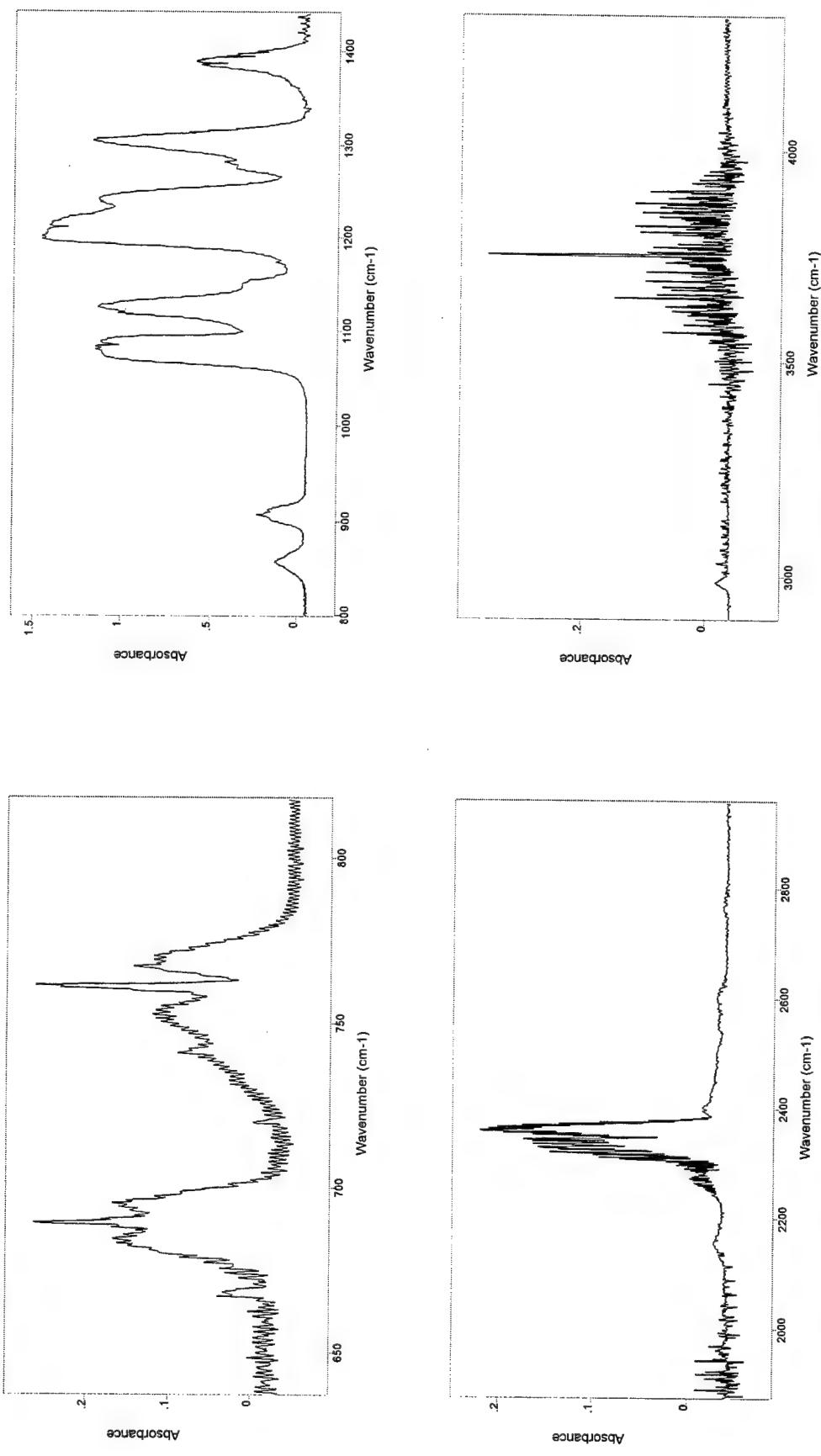


Figure 18. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FM-200 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510° C.

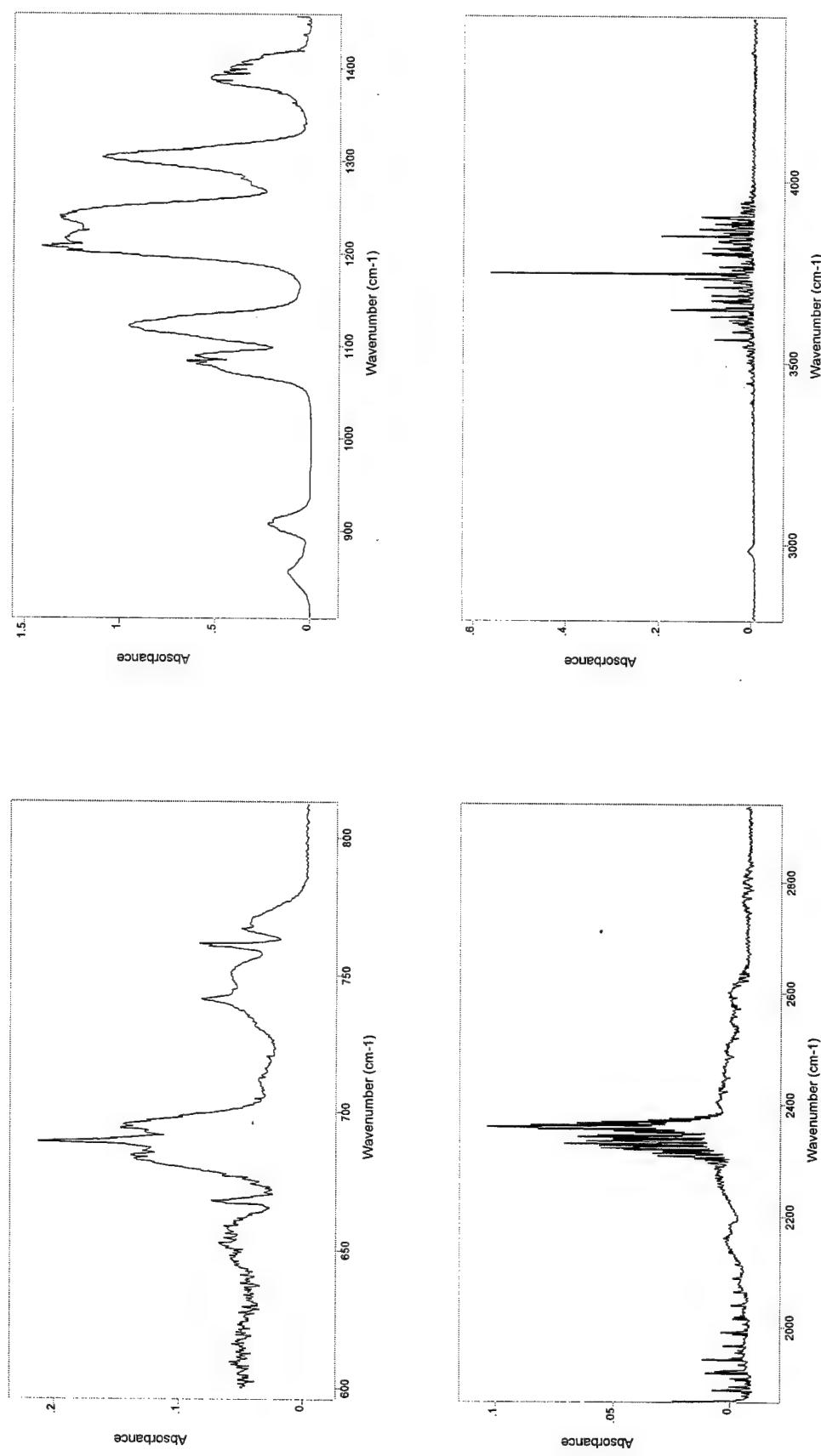


Figure 19. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-36 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380°C.

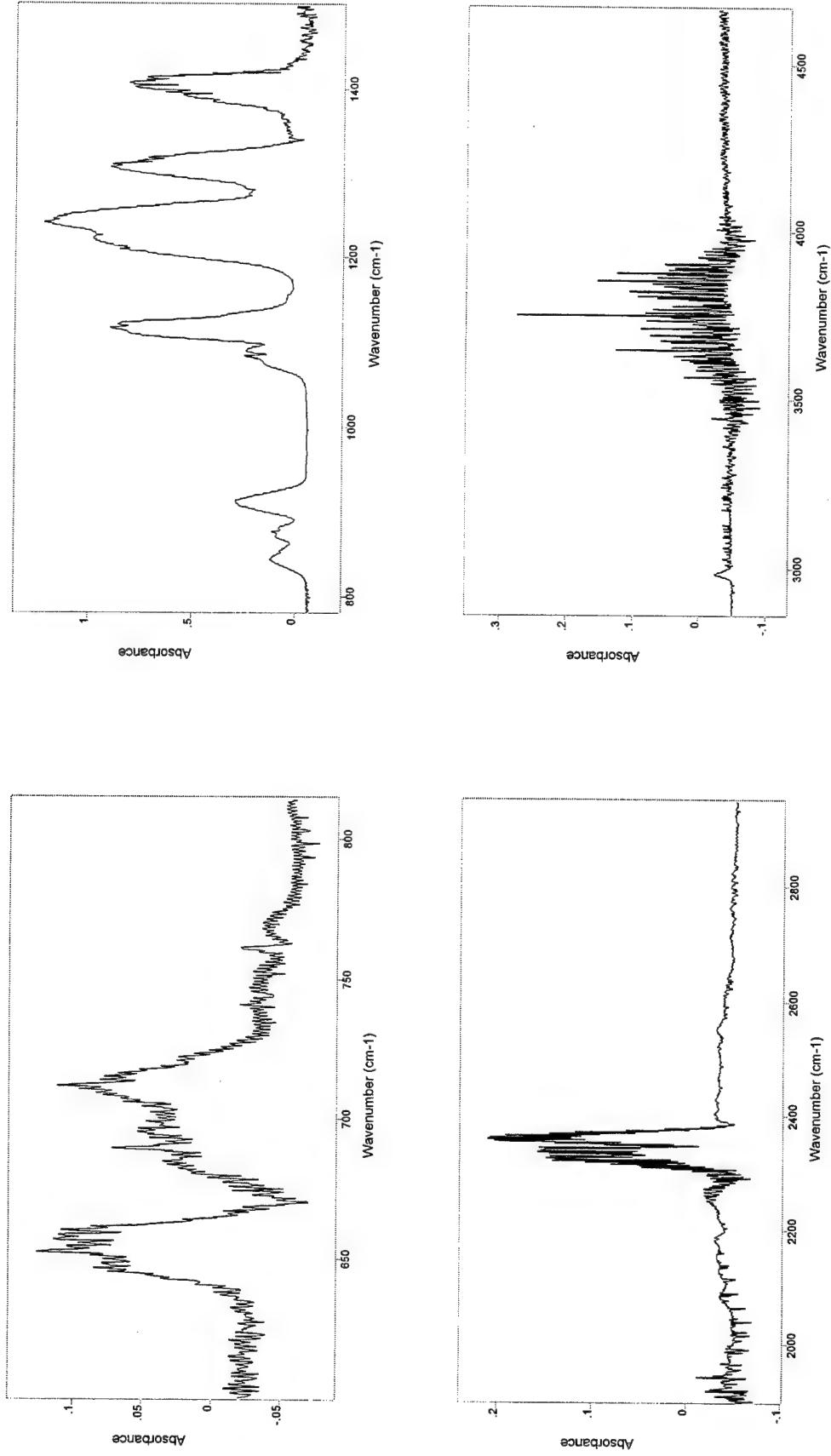


Figure 20. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-36 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510°C.

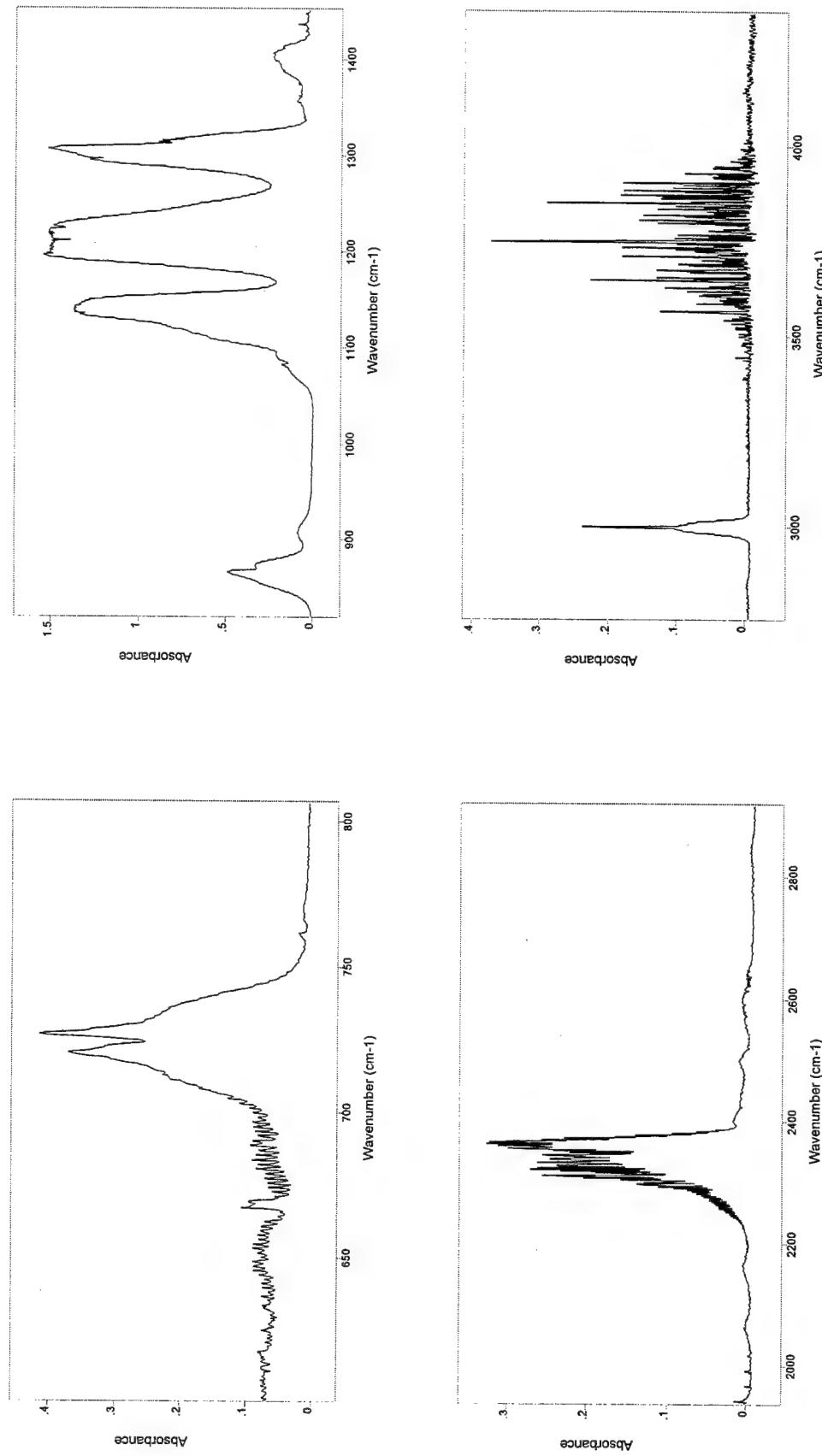


Figure 21. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-25 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380°C.

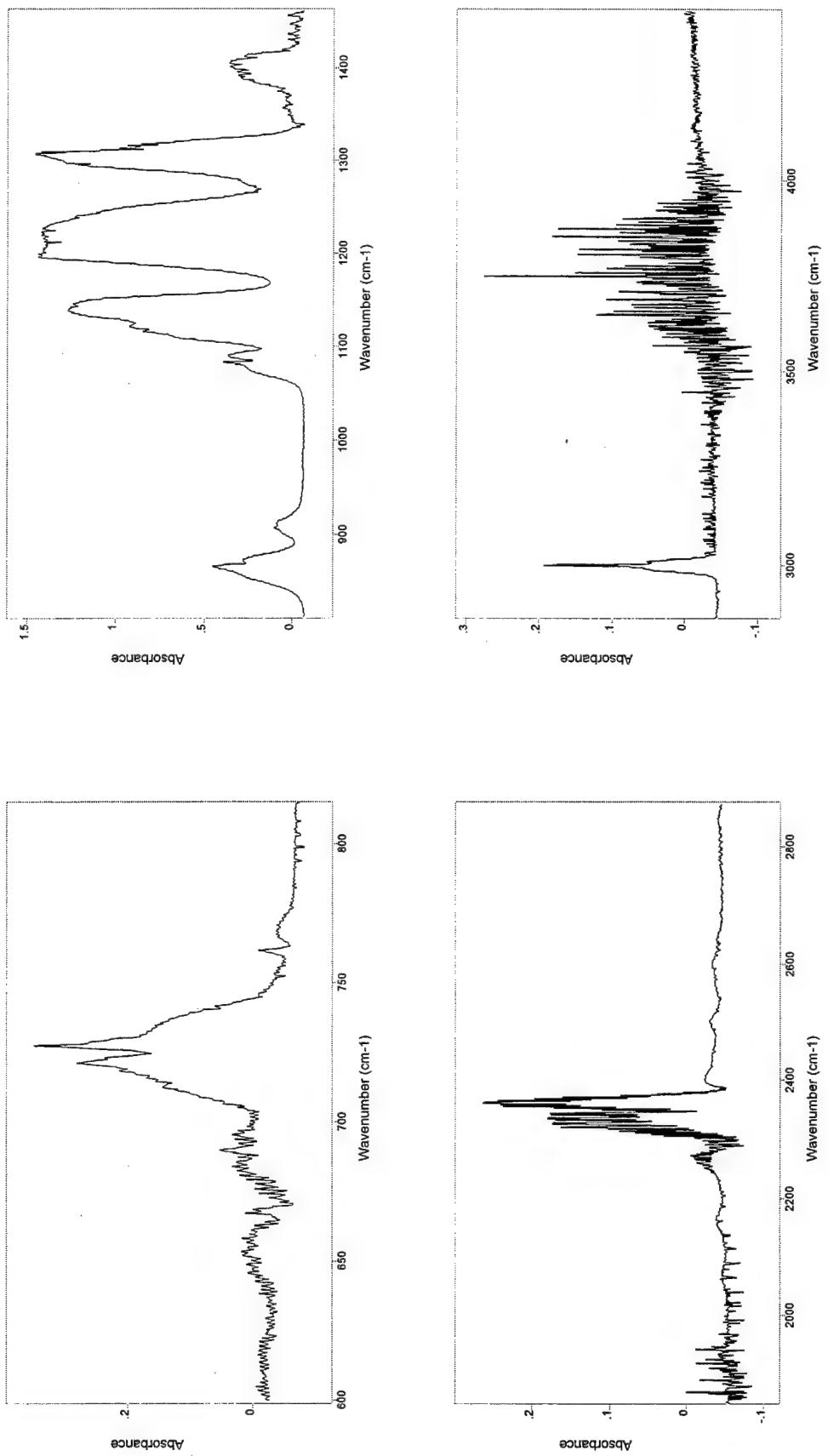
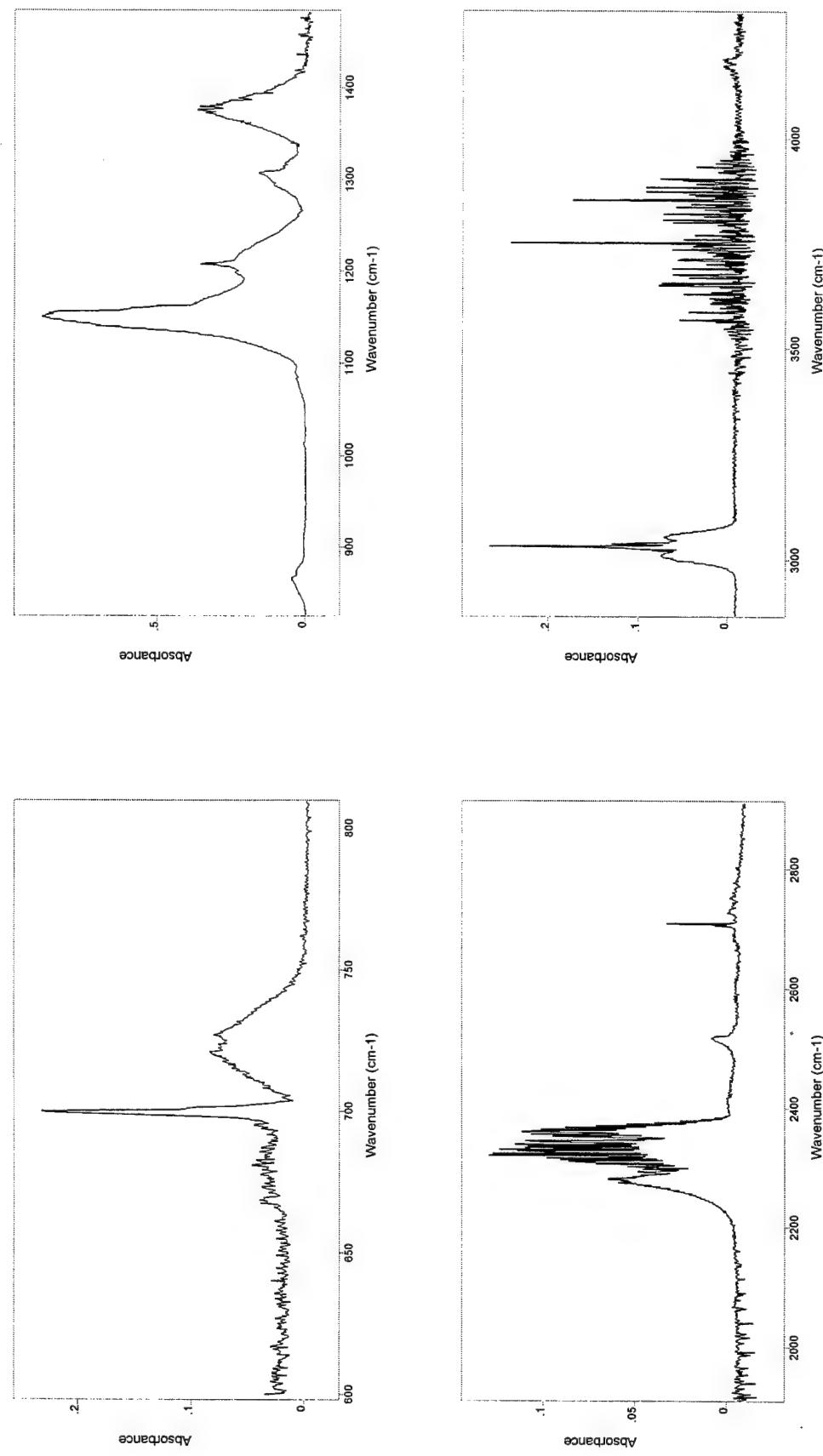
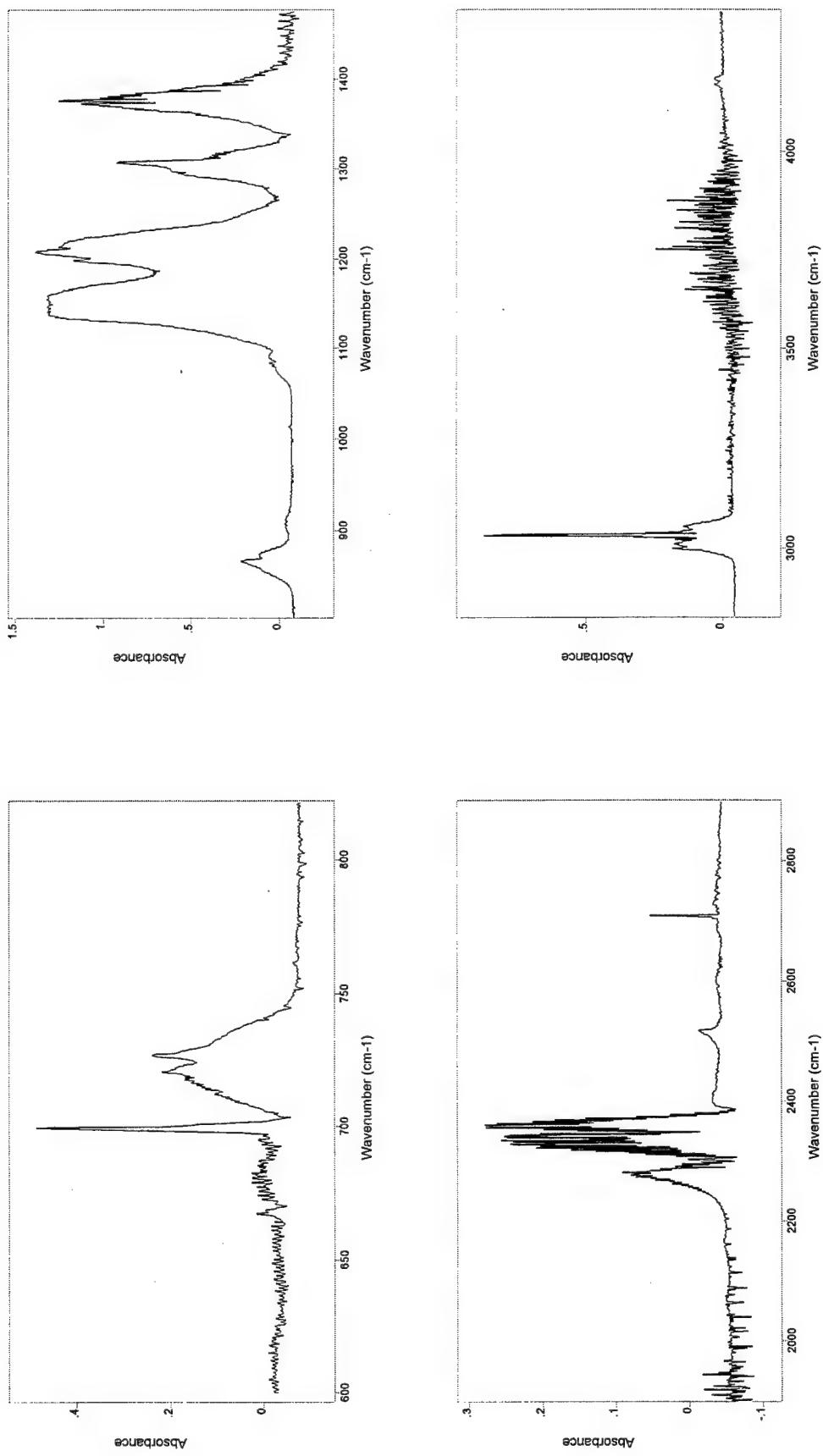


Figure 22. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-25 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510° C.



**Figure 23. Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire extinguishing agent FE-13 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 380° C.**



**Figure 24.** Expanded regions of the infrared absorbance spectrum of a gas sample removed from the personnel heater exit port while the fire-extinguishing agent FE-13 is flowed across the heat exchanger manifold. The heat exchanger manifold temperature was maintained at 480–510° C.

Table 1. Minimum Detection Limits for the Possible Decomposition Products of Interest

Species	Concentration (ppm)
HF	0.75
HBr	4.0
CF <sub>2</sub> O	0.27
CO	0.74
CH <sub>4</sub>	0.12
C <sub>2</sub> H <sub>2</sub>	0.11
C <sub>2</sub> H <sub>4</sub>	0.52
HC1	0.82

**INTENTIONALLY LEFT BLANK.**

## 5. REFERENCES

Federal Register, vol. 57, no. 11, pp. 1992-2005, 16 January 1992.

Infrared Analysis Inc. QASOFT for Grams, Anaheim, CA, 1995.

Modiano, S. H., K. L. McNesby, P. S. Marsh, W. Bolt, and C. Herud. "Quantitative Measurement of Toxic Gas Production During Inhibition of JP-8 Fires by CF<sub>3</sub>Br and C<sub>3</sub>F<sub>7</sub>H." Applied Optics, to be published.

National Institute of Standards and Technology. NIST/EPA Gas Phase Infrared Library. NIST Standard Reference Database 35, Gaithersburg, MD, May 1992.

Philipczak, R. A. "Relative Extinguishment Effectiveness and Agent Decomposition Products of Halon Alternative Agents." Proceedings of the 1993 Halon Options Technical Working Conference, New Mexico Engineering Research Institute, Albuquerque, NM, pp. 149-159, 1993.

Rothman, L. S., R. R. Gamache, R. H. Tipping, C. P. Rinsland, M. A. H. Smith, D. C. Brenner, V. Malathy Devi, J.-M. Flaud, C. Camy-Peyret, A. Perrin, A. Goldman, S. T. Massie, L. R. Brown, and R. A. Toth. "The HITRAN Molecular Database: Editions of 1991 and 1992." Journal Quant. Spectrosc. Radiat. Transfer, vol. 48, no. 5/6, p. 469, 1992.

Wray, T. K. "Halon." Hazmat World, p. 86, April 1992.

**INTENTIONALLY LEFT BLANK.**

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	DEFENSE TECHNICAL INFO CTR ATTN DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TL 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL OP SD TP 2800 POWDER MILL RD ADELPHI MD 20783-1145

ABERDEEN PROVING GROUND

2 DIR USARL  
ATTN AMSRL OP AP L (305)

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	HQDA ATTN SARD TT DR F MILTON PENTAGON WASHINGTON DC 20310-0103	1	OFFICE OF NAVAL RESEARCH DEPARTMENT OF THE NAVY ATTN R S MILLER CODE 432 800 N QUINCY STREET ARLINGTON VA 22217
1	HQDA ATTN SARD TT MR J APPEL PENTAGON WASHINGTON DC 20310-0103	1	COMMANDER NAVAL AIR SYSTEMS COMMAND ATTN J RAMNARACE AIR 54111C WASHINGTON DC 20360
1	HQDA OASA RDA ATTN DR C H CHURCH PENTAGON ROOM 3E486 WASHINGTON DC 20310-0103	2	COMMANDER NAVAL SURFACE WARFARE CENTER ATTN R BERNECKER R 13 G B WILMOT R 16 SILVER SPRING MD 20903-5000
4	COMMANDER US ARMY RESEARCH OFFICE ATTN R GHIRARDELLI D MANN R SINGLETON R SHAW P O BOX 12211 RSCH TRNGLE PK NC 27709-2211	5	COMMANDER NAVAL RESEARCH LABORATORY ATTN M C LIN J MCDONALD E ORAN J SHNUR R J DOYLE CODE 6110 WASHINGTON DC 20375
1	DIRECTOR ARMY RESEARCH OFFICE ATTN AMXRO RT IP LIB SERVICES P O BOX 12211 RSCH TRNGLE PK NC 27709-2211	2	COMMANDER NAVAL WEAPONS CENTER ATTN T BOGGS CODE 388 T PARR CODE 3895 CHINA LAKE CA 93555-6001
2	COMMANDER US ARMY ARDEC ATTN SMCAR AEE B D S DOWNS PCTNY ARSRL NJ 07806-5000	1	SUPERINTENDENT NAVAL POSTGRADUATE SCHOOL DEPT OF AERONAUTICS ATTN D W NETZER MONTEREY CA 93940
2	COMMANDER US ARMY ARDEC ATTN SMCAR AEE J A LANNON PCTNY ARSRL NJ 07806-5000	3	AL LSCF ATTN R CORLEY R GEISLER J LEVINE EDWARDS AFB CA 93523-5000
1	COMMANDER US ARMY ARDEC ATTN SMCAR AEE BR L HARRIS PCTNY ARSRL NJ 07806-5000	1	AFOSR ATTN J M TISHKOFF BOLLING AIR FORCE BASE WASHINGTON DC 20332
2	COMMANDER US ARMY MISSILE COMMAND ATTN AMSMI RD PR E A R MAYKUT AMSMI RD PR P R BETTS REDSTONE ARSENAL AL 35809		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	OSD SDIO IST ATTN L CAVENY PENTAGON WASHINGTON DC 20301-7100	3	DIRECTOR SANDIA NATIONAL LABORATORIES DIVISION 8354 ATTN S JOHNSTON P MATTERN D STEPHENSON LIVERMORE CA 94550
1	COMMANDANT USAFAS ATTN ATSF TSM CN FORT SILL OK 73503-5600	1	BRIGHAM YOUNG UNIVERSITY DEPT OF CHEMICAL ENGINEERING ATTN M W BECKSTEAD PROVO UT 84058
1	UNIV OF DAYTON RSCH INSTITUTE ATTN D CAMPBELL AL PAP EDWARDS AFB CA 93523	1	CALIFORNIA INSTITUTE OF TECH JET PROPULSION LABORATORY ATTN L STRAND MS 125 224 4800 OAK GROVE DRIVE PASADENA CA 91109
1	NASA LANGLEY RESEARCH CENTER ATTN G B NORTHAM MS 168 LANGLEY STATION HAMPTON VA 23365	1	CALIFORNIA INSTITUTE OF TECHNOLOGY ATTN F E C CULICK MC 301 46 204 KARMAN LAB PASADENA CA 91125
4	NATIONAL BUREAU OF STANDARDS US DEPARTMENT OF COMMERCE ATTN J HASTIE M JACOX T KASHIWAGI H SEMERJIAN WASHINGTON DC 20234	1	UNIVERSITY OF CALIFORNIA LOS ALAMOS SCIENTIFIC LAB P O BOX 1663 MAIL STOP B216 LOS ALAMOS NM 87545
2	DIRECTOR LAWRENCE LIVERMORE NATIONAL LAB ATTN C WESTBROOK W TAO MS L 282 P O BOX 808 LIVERMORE CA 94550	1	UNIVERSITY OF CALIFORNIA BERKELEY CHEMISTRY DEPARMENT ATTN C BRADLEY MOORE 211 LEWIS HALL BERKELEY CA 94720
1	DIRECTOR LOS ALAMOS NATIONAL LAB ATTN B NICHOLS T7 MS B284 P O BOX 1663 LOS ALAMOS NM 87545	1	UNIVERSITY OF CALIFORNIA SAN DIEGO ATTN F A WILLIAMS AMES B010 LA JOLLA CA 92093
2	PRINCETON COMBUSTION RESEARCH LABORATORIES INC ATTN N A MESSINA M SUMMERFIELD PRINCETON CORPORATE PLAZA BLDG IV SUITE 119 11 DEERPARK DRIVE MONMOUTH JUNCTION NJ 08852	2	UNIV OF CALIFORNIA SANTA BARBARA QUANTUM INSTITUTE ATTN K SCHOFIELD M STEINBERG SANTA BARBARA CA 93106
		1	UNIV OF COLORADO AT BOULDER ENGINEERING CENTER ATTN J DAILY CAMPUS BOX 427 BOULDER CO 80309-0427

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
3	UNIV OF SOUTHERN CALIFORNIA DEPT OF CHEMISTRY ATTN R BEAUDET S BENSON C WITTIG LOS ANGELES CA 90007	4	PENNSYLVANIA STATE UNIVERSITY DEPT OF MECHANICAL ENGINEERING ATTN K KUO M MICCI S THYNELL V YANG UNIVERSITY PARK PA 16802
1	CORNELL UNIVERSITY DEPARTMENT OF CHEMISTRY ATTN T A COOL BAKER LABORATORY ITHACA NY 14853	2	PRINCETON UNIVERSITY FORRESTAL CAMPUS LIBRARY ATTN K BREZINSKY I GLASSMAN P O BOX 710 PRINCETON NJ 08540
1	UNIVERSITY OF DELAWARE CHEMISTRY DEPARTMENT ATTN T BRILL NEWARK DE 19711	1	PURDUE UNIVERSITY SCHL OF AERONAUTICS & ASTRONAUTICS ATTN J R OSBORN GRISOM HALL WEST LAFAYETTE IN 47906
1	UNIVERSITY OF FLORIDA DEPT OF CHEMISTRY ATTN J WINEFORDNER GAINESVILLE FL 32611	1	PURDUE UNIVERSITY DEPARTMENT OF CHEMISTRY ATTN E GRANT WEST LAFAYETTE IN 47906
3	GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF AEROSPACE ENGINEERING ATTN E PRICE W C STRAHLE B T ZINN ATLANTA GA 30332	2	PURDUE UNIVERSITY SCHL OF MECHANICAL ENGNRNG ATTN N M LAURENDEAU S N B MURTHY TSPC CHAFFEE HALL WEST LAFAYETTE IN 47906
1	UNIVERSITY OF ILLINOIS DEPT OF MECH ENG ATTN H KRIER 144MEB 1206 W GREEN ST URBANA IL 61801	1	RENSSELAER POLYTECHNIC INST DEPT OF CHEMICAL ENGINEERING ATTN A FONTIJN TROY NY 12181
1	THE JOHNS HOPKINS UNIV CPIA ATTN T W CHRISTIAN 10630 LITTLE PATUXENT PKWY SUITE 202 COLUMBIA MD 21044-3200	1	STANFORD UNIVERSITY DEPT OF MECHANICAL ENGINEERING ATTN R HANSON STANFORD CA 94305
1	UNIVERSITY OF MICHIGAN GAS DYNAMICS LAB ATTN G M FAETH AEROSPACE ENGINEERING BLDG ANN ARBOR MI 48109-2140	1	UNIVERSITY OF TEXAS DEPT OF CHEMISTRY ATTN W GARDINER AUSTIN TX 78712
1	UNIVERSITY OF MINNESOTA DEPT OF MECHANICAL ENGINEERING ATTN E FLETCHER MINNEAPOLIS MN 55455	1	VA POLYTECH INST AND STATE UNIV ATTN J A SCHETZ BLACKSBURG VA 24061

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	APPLIED COMBUSTION TECHNOLOGY INC ATTN A M VARNEY P O BOX 607885 ORLANDO FL 32860	1	HERCULES INC ATTN R V CARTWRIGHT 100 HOWARD BLVD KENVIL NJ 07847
2	APPLIED MECHANICS REVIEWS ASME ATTN R E WHITE & A B WENZEL 345 E 47TH STREET NEW YORK NY 10017	1	ALLIANT TECHSYSTEMS INC MARINE SYSTEMS GROUP ATTN D E BRODEN MS MN50 2000 600 2ND STREET NE HOPKINS MN 55343
1	TEXTRON DEFENSE SYSTEMS ATTN A PATRICK 2385 REVERE BEACH PARKWAY EVERETT MA 02149-5900	1	ALLIANT TECHSYSTEMS INC ATTN R E TOMPKINS MN 11 2720 600 SECOND ST NORTH HOPKINS MN 55343
1	BATTELLE TWSTIAC 505 KING AVENUE COLUMBUS OH 43201-2693	1	IBM CORPORATION RESEARCH DIVISION ATTN A C TAM 5600 COTTLE ROAD SAN JOSE CA 95193
1	COHEN PROFESSIONAL SERVICES ATTN N S COHEN 141 CHANNING STREET REDLANDS CA 92373	1	IIT RESEARCH INSTITUTE ATTN R F REMALY 10 WEST 35TH STREET CHICAGO IL 60616
1	EXXON RESEARCH & ENG CO ATTN A DEAN ROUTE 22E ANNANDALE NJ 08801	1	LOCKHEED MISSILES & SPACE CO ATTN GEORGE LO 3251 HANOVER STREET DEPT 52 35 B204 2 PALO ALTO CA 94304
1	GENERAL APPLIED SCIENCE LABS INC 77 RAYNOR AVENUE RONKONKAMA NY 11779-6649	1	OLIN ORDNANCE ATTN V McDONALD LIBRARY P O BOX 222 ST MARKS FL 32355-0222
1	GENERAL ELECTRIC ORDNANCE SYSTEMS ATTN J MANDZY 100 PLASTICS AVENUE PITTSFIELD MA 01203	1	PAUL GOUGH ASSOCIATES INC ATTN P S GOUGH 1048 SOUTH STREET PORTSMOUTH NH 03801-5423
1	GENERAL MOTORS RSCH LABS PHYSICAL CHEMISTRY DEPARTMENT ATTN T SLOANE WARREN MI 48090-9055	1	HUGHES AIRCRAFT COMPANY ATTN T E WARD PO BOX 11337 TUCSON AZ 85734-1337
2	HERCULES INC ATTN W B WALKUP E A YOUNT P O BOX 210 ROCKET CENTER WV 26726		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	SCIENCE APPLICATIONS INC ATTN R B EDELMAN 23146 CUMORAH CREST WOODLAND HILLS CA 91364	1	UNIVERSAL PROPULSION COMPANY ATTN H J MCSPADEN 25401 NORTH CENTRAL AVENUE PHOENIX AZ 85027-7837
3	SRI INTERNATIONAL ATTN G SMITH D CROSLEY D GOLDEN 333 RAVENSWOOD AVENUE MENLO PARK CA 94025	1	VERITAY TECHNOLOGY INC ATTN E B FISHER 4845 MILLERSPORT HIGHWAY EAST AMHERST NY 14051-0305
1	STEVENS INSTITUTE OF TECH DAVIDSON LABORATORY ATTN R MCALEVY III HOBOKEN NJ 07030	1	FREEDMAN ASSOCIATES ATTN E FREEDMAN 2411 DIANA ROAD BALTIMORE MD 21209-1525
1	SVERDRUP TECHNOLOGY INC LERC GROUP ATTN R J LOCKE MS SVR 2 2001 AEROSPACE PARKWAY BROOK PARK OH 44142	3	ALLIANT TECHSYSTEMS ATTN C CANDLAND L OSGOOD R BECKER 600 SECOND ST NE HOPKINS MN 55343
1	SVERDRUP TECHNOLOGY INC ATTN J DEUR 2001 AEROSPACE PARKWAY BROOK PARK OH 44142	1	DIRECTOR US ARMY BENET LABS ATTN AMSTA AR CCB T SAM SOPOK WATERVLIET NY 12189
3	THIOKOL CORPORATION ELKTON DIVISION ATTN R BIDDLE R WILLER TECH LIB P O BOX 241 ELKTON MD 21921		
3	THIOKOL CORPORATION WASATCH DIVISION ATTN S J BENNETT P O BOX 524 BRIGHAM CITY UT 84302		
1	UNITED TECHNOLOGIES RSCH CENTER ATTN A C ECKBRETH EAST HARTFORD CT 06108		
1	UNITED TECHNOLOGIES CORP CHEMICAL SYSTEMS DIVISION ATTN R R MILLER P O BOX 49028 SAN JOSE CA 95161-9028		

NO. OF  
COPIES ORGANIZATION

ABERDEEN PROVING GROUND

36 DIR USARL  
ATTN: AMSRL-WT-P, A HORST  
AMSRL-WT-PC,  
R A FIFER  
G F ADAMS  
W R ANDERSON  
R A BEYER  
S W BUNTE  
C F CHABAŁOWSKI  
K P MCNEILL-BOONSTOPPEL  
A COHEN  
R CUMPTON  
R DANIEL  
D DEVYNCK  
N F FELL  
B E FORCH  
J M HEIMERL  
A J KOTLAR  
M R MANAA  
W F MCBRATNEY  
K L MCNESBY  
S V MEDLIN  
M S MILLER  
A W MIZIOLEK  
S H MODIANO  
J B MORRIS  
J E NEWBERRY  
S A NEWTON  
R A PESCE-RODRIGUEZ  
B M RICE  
R C SAUSA  
M A SCHROEDER  
J A VANDERHOFF  
M WENSING  
A WHREN  
J M WIDDER  
C WILLIAMSON  
AMSRL-CI-CA, R PATEL

**INTENTIONALLY LEFT BLANK.**

## USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1207 (McNesby) Date of Report October 1996

2. Date Report Received \_\_\_\_\_

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.)  
\_\_\_\_\_  
\_\_\_\_\_

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.)  
\_\_\_\_\_  
\_\_\_\_\_

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate.  
\_\_\_\_\_  
\_\_\_\_\_

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.)  
\_\_\_\_\_  
\_\_\_\_\_

CURRENT  
ADDRESS

Organization \_\_\_\_\_  
Name \_\_\_\_\_  
Street or P.O. Box No. \_\_\_\_\_  
City, State, Zip Code \_\_\_\_\_

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD  
ADDRESS

Organization \_\_\_\_\_  
Name \_\_\_\_\_  
Street or P.O. Box No. \_\_\_\_\_  
City, State, Zip Code \_\_\_\_\_

(Remove this sheet, fold as indicated, tape closed, and mail.)  
**(DO NOT STAPLE)**